...ctivity Estimation and Validation for the Control of Reactor Neutronic Power

by

CHARLES STANLEY LASOTA

B.S., Electrical Engineering
University of Kansas, 1985

Submitted to the Departments of Nuclear Engineering and Electrical Engineering and Computer Science in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Nuclear Engineering
and
Master of Science in Electrical Engineering and Computer Science

at the
Massachusetts Institute of Technology
May 1993

Signature of Author Charles S LaSota

Certified by
Dr. John A. Bernard, Jr., MIT NRL, Thesis Co-Advisor

Certified by David D Lanning
David D. Lanning, Professor of Nuclear Engineering, Thesis Co-Advisor

Certified by Marija Ilic'
Dr. Marija Ilic', Senior Research Scientist, Thesis Reader
Department of Electrical Engineering and Computer Science

Accepted by
Campbell L. Searle, Chair, EECS Committee on Graduate Students

Accepted by A F Henry
Allan F. Henry, Chairman, NED Committee on Graduate Students

Reactivity Estimation and Validation for the Control of Reactor Neutronic Power

by

Charles Stanley LaSota

Submitted to the Departments of Nuclear Engineering and Electrical Engineering and Computer Science on the 7th of May 1993 in partial fulfillment of the requirements for the degrees of Master of Science in Nuclear Engineering and Master of Science in Electrical Engineering and Computer Science.

Abstract

From July 1986 to July 1991, a joint MIT-SNL research team developed a controller capable of safely raising reactor power by approximately five orders of magnitude in a few seconds. This controller was experimentally demonstrated on the MIT Research Reactor (MITR-II) as well as on the Sandia National Laboratories' Annular Core Research Reactor (ACRR). This controller's intended application is for the control of spacecraft nuclear reactors. However, it also has direct application for the control of military, commercial, and research reactors.

This report is concerned with a method for enhancing the controller's performance through the development of an improved model to validate estimates of the magnitude of reactivity feedback effects. The focus is on the Doppler effect but the resulting model is applicable to other types of reactivity feedback such as that associated with the thermal effects of a hydrogen coolant. The specific accomplishments of this report include:

1. The development of a reactor model that generates analytic values of reactivity resulting from reactor temperature variation.

2. The development of an adaptive estimation routine to correct deficiencies in the reactor model so that the model generates the validated estimate of reactivity in real time. (Note: For the purpose of this report the inverse kinetics estimate of reactivity is assumed to be correct).

3. Application of a parity space approach to provide for validation of assumed independent reactivity inputs.

4. Performance of system analysis to determine the minimum number of sensor inputs to implement the closed form control laws and still allow for automated fault diagnosis.

5. Demonstrations of the adaptive estimation routine for reactivity.

Thesis Co-Advisor: Dr. John A. Bernard Jr.

Title: Director of Reactor Operations

Thesis Co-Advisor: Professor David D. Lanning

Title: Professor of Nuclear Engineering

Thesis Reader: Dr. Marija Ilic'

Title: Senior Research Scientist,
Department of Electrical Engineering and Computer Science

Dedication

This Report is dedicated to my loving wife Donna and our son Matthew. I am deeply indebted to them for their support, love and understanding during the past two years. I would also like to thank my wife Donna for her help in preparing this report. Her many hours of typing, proof reading and preparing charts helped make the timely completion of this report possible.

Acknowledgments

The author wishes to offer his sincere gratitude to Dr. John A. Bernard, Dr. Marija Ilic' and Professor David D. Lanning for their guidance, assistance and understanding during the development of this report. Their willingness to discuss this work on a moments notice and their many beneficial suggestions were greatly appreciated.

I also wish to express my thanks to all the other individuals who offered information, advice and recommendations that were invaluable to the formulation of this report. Some of these individuals include: Professor John Meyer for his assistance in the formulation and evaluation of the reactor heat deposition model; Professor George Verghese for his assistance in developing the extended Kalman estimation routine for model adaptation; Mr. Mitch McCrory of the Reactor Applications Department at Sandia National Laboratories for his help in obtaining design data for the Annular Core Research Reactor (ACRR) for model implementation; and Mrs. Carolyn Hinds for her helpful tips on report organization and layout.

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES AND TABLES

1. Introduction

1.1 Objectives

This report describes the theoretical analysis and evaluation through computer simulations of an improved reactivity estimation and validation scheme. The use of an adaptive reactivity model represents a potential improvement to the MIT-SNL Period-Generated Minimum Time Reactor Neutronic Power Controller [1]. The MIT-SNL control scheme has been successfully demonstrated on both the MIT Research Reactor (MITR-II) and the Sandia National Laboratories' Annular Core Research Reactor (ACRR). These demonstrations showed the controller to be capable of changing reactor power by approximately five orders of magnitude in a few seconds. Thermal feedback reactivity is one of several inputs required to determine the proper rod control response to achieve a desired power level. Experiments conducted on the Annular Core Research Reactor (ACRR) *during the period* July 1986 *to* July 1991 revealed that estimates of the thermal feedback reactivity calculated via correlation to measured reactor fuel temperature were not always accurate. These inaccuracies were traceable to time delays associated with the temperature measurement process [2].

The reactivity estimation routine developed here uses an energy deposition model with reactor power as its input signal. In addition to incorporating a more responsive input signal, this reactivity estimation routine makes use of adaptive Kalman estimation. This corrects the model for errors in the time-dependent behavior of the feedback reactivity model's thermal-hydraulic parameters. The input to the Kalman estimation routine is a reactivity signal obtained by applying the parity space validation approach to

three reactivity signals that are assumed to be independent [3]. Chapter Two discusses the source of these signals.

A system analysis of the MIT-SNL Controller is also made to determine the minimum number of sensor inputs necessary to implement the MIT-SNL closed form control laws and allow for automated fault diagnosis.

1.2 Background

This report deals with an enhancement to the MIT-SNL period-generated, minimum-time reactor neutronic power controller. This controller's intended use is for the control of spacecraft nuclear reactors. However, it also has direct applications for the control of military, commercial, and research reactors. The theoretical analysis of the adaptive reactivity estimation model is generic in derivation. The simulations for model verification use the Annular Core Research Reactor for implementation.

1.2.1 The MIT-SNL Minimum-Time Controller

The MIT-SNL minimum-time neutronic power controller has as its basis the MIT-SNL minimum-time control laws. The derivation of the minimum-time control laws, their implementation as the basis for a reactor power controller, and the subsequent experimental evaluation of the controller are described in detail in "Formulation and Experimental Evaluation of Closed-Form Control Laws for the Rapid Maneuvering of Reactor Power" and "Startup and Control of Nuclear Reactors Characterized by Space-Independent Kinetics". These reports, by Dr. John A. Bernard Jr., trace the MIT-SNL minimum-time neutronic power controller through its development and initial experimental

evaluation. The current status of the controller is given in two recent publications [4,5]. The MIT-SNL control laws are a form of period-generated control. The latter is a technique developed at MIT for the purpose of adjusting reactor neutronic power in a rapid yet safe manner. It is a method for tracking trajectories that are defined in terms of a demanded rate and has been shown through experiment to offer superior performance as compared to other forms of model-based feedforward/feedback control [6]. There are four major steps in its implementation. First, an error signal is defined by comparison of the observed process output with that which was specified. Second, a demanded inverse period (a velocity) is generated in terms of the error signal. Third, the demanded inverse period is processed through a system model to obtain the requisite control signal. Fourth, the control signal is applied to the actual system. Advantages to period-generated control are that it is readily implemented, that it is model-based and hence can be applied to non-linear systems, and that the resulting control laws may approach time-optimal behavior for the special case of rate-constrained processes. The calculational sequence to apply period-generated control is as follows:

1. Determine the error between the observed and specified reactor powers.

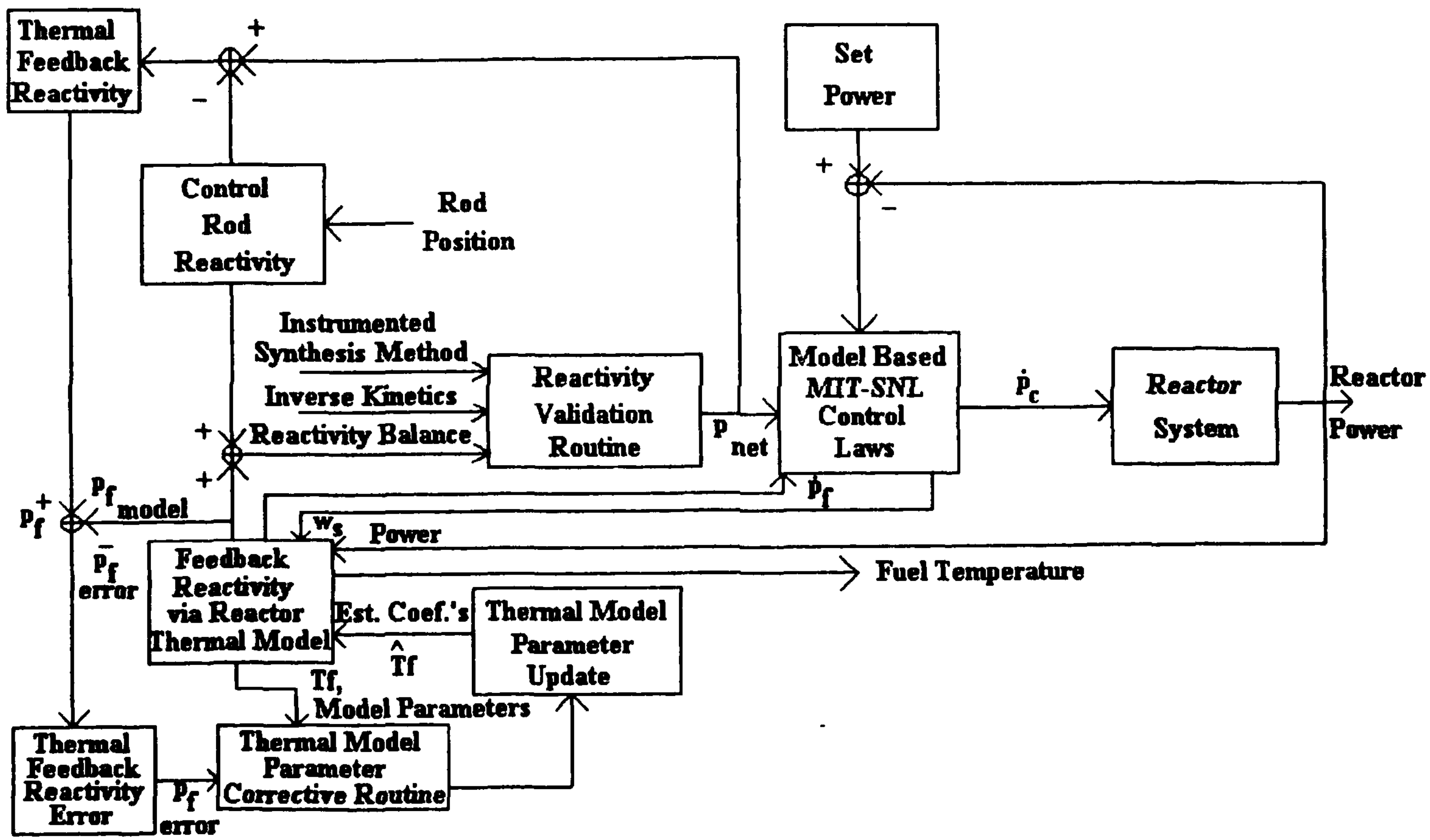
2. Calculate the period needed to return the error to zero.

3. Obtain the rate of change of reactivity needed to generate the period calculated above. This is done by processing the calculated period using an inverse kinetics reactivity model of the reactor.

4. Apply the calculated rate of reactivity to the reactor via the reactivity control system.

Implementation of this calculational sequence requires that both the net reactivity and the rate of change of reactivity associated with thermal feedback be known. The adaptive reactivity model will provide a signal source for the rate of reactivity change due to thermal feedback as well as providing a feedback reactivity signal to a reactivity balance. This reactivity balance will supply one of three reactivity signals needed for reactivity validation. The use of the adaptive reactivity model for use in the MIT-SNL Neutronic Power Controller is shown in Figure 1.2.1-1.

Figure 1.2.1-1 Reactor Neutronic Power Controller Block Diagram



1.2.2 Annular Core Research Reactor

The equations that comprise the adaptive reactivity model are generic. However, the model simulations and subsequent software development that was done to evaluate the model are applicable to the Annular Core Research Reactor (ACRR) that is operated by Sandia National Laboratories. This was done to support continued controller evaluation and testing at the ACRR.

The ACRR is a modified TRIGA. Its core contains two hundred thirty-six UO_2 - BeO fuel elements arranged to form a hexagonal grid around a 23 cm annulus. The reactor is capable of operating in either a steady-state or a pulse mode. The maximum allowed power level for steady-state operation is two megawatts. Limits for pulse mode operations are 1800° C. fuel temperature and 500 MJ of total energy per pulse.

The ACRR fuel elements are of a unique design. The fuel pellets are formed in two concentric rings about a center void. These fuel pellet rings are loaded into corrugated niobium cups. The niobium forms a refractory inner liner to retain the heat generated by the fission process and thereby ensure rapidly rising fuel temperatures. This is a safety feature because the fuel possesses a large negative reactivity coefficient which maybe used to shut the reactor down following a reactivity pulse. The reactivity coefficient of the fuel is further described in Chapter Three. A cut away view of the ACRR Core is shown in Figure 1.2.2-1.

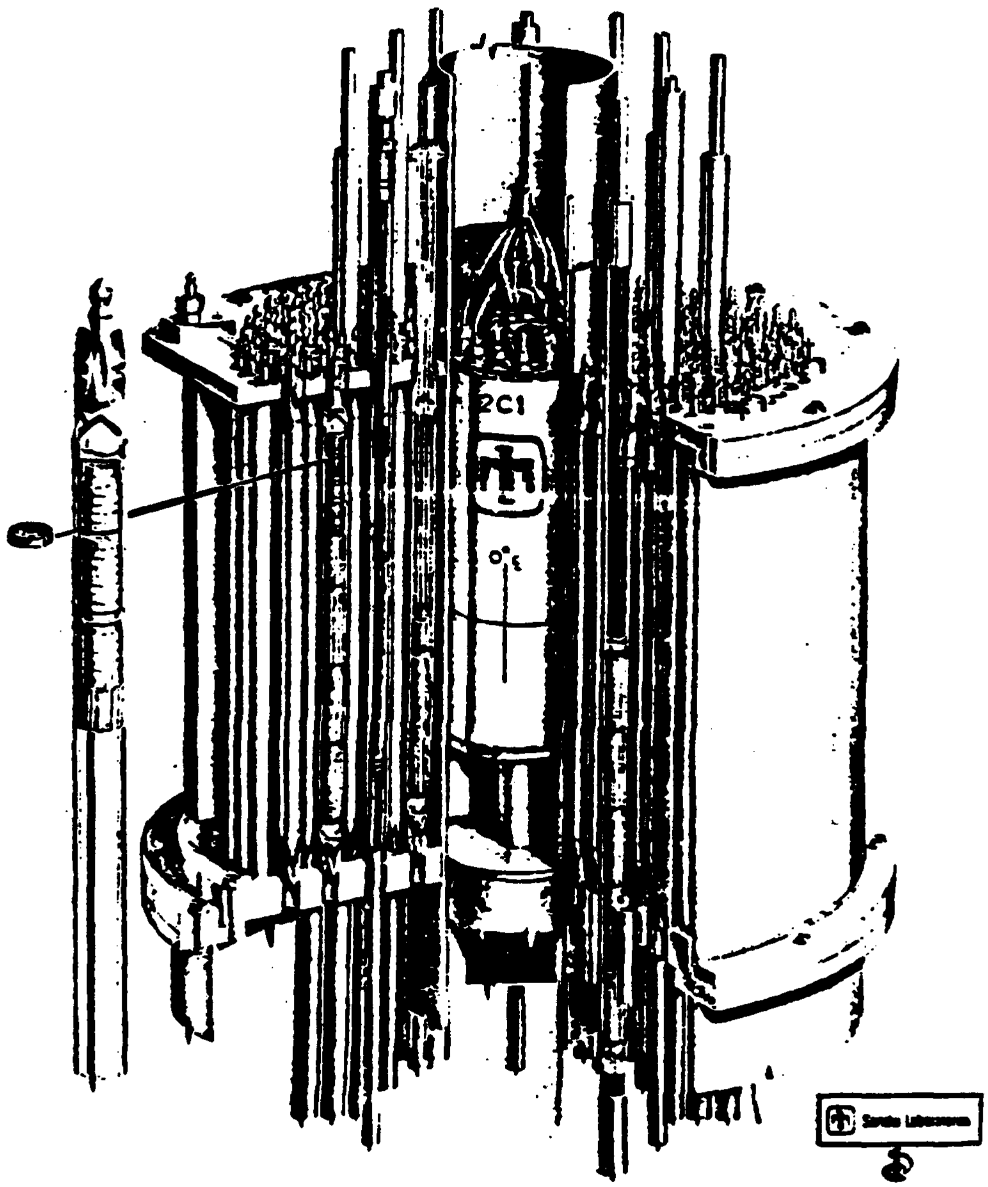


Figure 1.2.2-1 Cutaway View of ACRR Core

1.3 Organization of Report

This report describes the theoretical analysis and simulation evaluation for the adaptive reactivity model for the enhanced operation of the MIT-SNL neutronic power controller. Chapter Two defines the methods of reactivity measurement used for implementation of the neutronic power controller. It also develops the equations used to implement the reactivity balance model for predicting feedback reactivity from reactor temperature variations. Chapter Three derives the equations needed to implement the heat deposition model of the reactor core that was used to generate analytic values of fuel temperature. Chapter Four develops the estimation routine needed to obtain the reactivity model adaptation to compensate for modeling errors and the time-varying nature of the thermal-hydraulic parameters. Equation derivations cover the basic principle of minimum variance estimation, Kalman estimation, and the extension of Kalman estimation techniques to non-linear systems. Chapter Five describes the simulations used to verify the effectiveness of the modeling techniques proposed for use in the adaptive reactivity model. Chapter Six describes the parity space validation used to estimate the reactivity from three independent sources. Chapter Seven addresses the FORTRAN program implementation of the adaptive reactivity model. Chapter Eight covers the final simulation of the FORTRAN program implementation of the reactivity balance model. Chapter Nine discusses sensor optimization for the minimum-time control laws. A system analysis is performed to determine the minimum sensor requirements for performing automatic system fault detection. Chapter Ten discusses areas of future research that would further enhance the operation of the adaptive reactivity model. The appendices contain sample input and output files used for reactivity model simulations.

2. Nuclear Reactor Reactivity Model

As described in Chapter One, determination of accurate values of both the thermal feedback reactivity and the net reactivity is required to implement the MIT-SNL period-generated minimum time control laws. In addition to these reactivity inputs, it is also necessary to establish the net rate of change of feedback reactivity. This permits calculation of the proper control signals for implementing reactor power transients. This chapter addresses the issues and methods of reactivity measurement used for reactor power control.

2.1 Definition of Reactivity

The "effective neutron multiplication factor", Keff, is used to characterize the state of a nuclear reactor. Keff is the ratio of neutrons produced from fission to those that are lost through leakage or absorption. Thus, for a critical reactor Keff would have a value of unity. Reactivity can be defined in terms of Keff. This definition is:

$$\rho \equiv \frac{\text{Keff} - 1}{\text{Keff}} \tag{2.1-1}$$

where ρ is the reactivity [7]. The reactivity can be thought of as the fractional deviation of the neutron population in the reactor per neutron generation or lifetime. It should be noted that both Keff and ρ are global properties that pertain to the reactor as a whole.

Reactivity is dimensionless, and is therefore usually expressed as a percentage. Reactivity may also be given as a multiple of the effective delayed neutron fraction, Beta. For example, a reactor with an effective delayed neutron fraction of 0.0073 and a reactivity of 0.0025 percent, would have reactivity of 0.342 Beta. Another system of "units" is dollars and cents with one dollar of reactivity being the equivalent of 1 Beta of reactivity. In the above example, the reactivity would be referred to as 34.2 cents of reactivity.

The above definition includes the time-dependence of reactivity. It should be noted that a more complete definition of reactivity would address both spatial and energy dependence. A definition of reactivity in terms of position, energy, and time is given in the following equation [8] :

$$\rho(t) \equiv \frac{\int dv \int dE\, W(r,E)[\nabla D(r,E,t)\nabla\Phi(r,E,t) - A\Phi(r,E,t) + \sum_j \chi^j(E) F^j \Phi(r,E,t)]}{\int dv \int dE\, W(r,E) \sum_j \chi^j(E) F^j \Phi(r,E,t)} \tag{2.1-2}$$

In this equation A and F are integral operators defined through their operation on any function f (r,E,t) with j denoting a particular fissionable isotope. These equations for the integral operations are [9] :

$$Af \equiv \Sigma_t(r,E,t)\, f(r,E,t) - \int_0^\infty \Sigma_s(r,E' \rightarrow E,t)\, f(r,E',t)dE' \tag{2.1-3}$$

$$F^j f \equiv \int_0^\infty \nu\Sigma_f^j(r,E',t)\, f(r,E',t)dE' \tag{2.1-4}$$

The remaining symbols are defined as:

W(r,E)	is the weighing factor for "Neutron Importance",
D(r,E,t)	is the diffusion coefficient,
Φ (r,E,t)	is the neutron flux density,
χ(E)	is the fission spectrum,
Σ_t(r,E,t)	is the total macroscopic cross section,
Σ_s(r,E'$\rightarrow$E,t)	is the macroscopic scattering cross section, and
Σ_f(r,Et)	is the macroscopic fission cross section.

The concept of reactivity as a time-position and energy-dependent quantity is important when developing methods for reactor reactivity estimation. A given estimation

method may assume reactor properties to be constant in energy throughout the core. While this may not be incorrect for a given set of reactor conditions, it must be recognized as a limitation of the method employed.

2.2 Assumptions In Reactivity Estimation

Presently two methods of reactivity measurement are widely employed. These are inverse kinetics and reactivity balances. These are further discussed in section 2.3. The major assumptions associated with these methods lead to the conclusion that reactivity can be calculated only as a function of time. The energy dependence in the inverse kinetics method is eliminated by use of the effective delayed neutron fraction, β_i. This method allows the energy dependence of the delayed neutrons to be described by the ratio of the "instantaneous" weighted rate of delayed neutron production divided by the "instantaneous" weighted rate of all neutron production due to fission [10]. The spatial dependence in the inverse kinetics method is eliminated through the assumption that the neutron flux, Φ, is a product of the flux shape, S, and a flux amplitude function, T. This relation is given by the following equation:

$$S(r,E,t)\,T(t) = \Phi(r,E,t) \tag{2.2-1}$$

Thus, if the flux shape is assumed not to change, and appropriate weighting functions are chosen, the estimation of the flux will be given by the amplitude function which depends on time alone.

The reactivity balance method also employs energy and spatial assumptions. The standard procedure is to determine reactivity coefficients through a specific experiment and/or theoretical calculation and then to apply these coefficients to a variety of reactor

conditions. In reality, the coefficients are only accurate for the given reactor flux shape and the set of conditions present when the coefficient calculation or measurement was performed. Comparisons of reactivities determined using different methods and assumptions must be carefully analyzed. Failure to ensure the validity of the underlying assumptions used in reactivity measurement could lead to an incorrect estimation of reactivity.

2.3 Reactivity Measurement Methods

The reactivity methods considered here for reactivity estimation and validation are:

- Inverse Kinetics
- Reactivity Balances
- Instrumented Synthesis

2.3.1 Inverse Kinetics

The Inverse Kinetics method of reactivity measurement is based on the space independent reactor kinetics or "point kinetics equations" [11]. These equations are:

$$\frac{dT(t)}{dt} = \frac{\rho(t) - \bar{\beta}}{\Lambda} T(t) + \sum_{i=1}^{I} \lambda_i C_i(t) + Q(t) \qquad (2.3.1\text{-}1)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda}T(t) - \lambda_i C_i(t) \qquad \text{for } i = 1,2,\ldots,I \qquad (2.3.1\text{-}2)$$

where: $T(t)$ is the neutron integral weighted flux amplitude function,

$Q(t)$ is the neutron weighted integral extraneous source term,

$\rho(t)$ is the net reactivity,

$\overline{\beta}$ is the effective delayed neutron fraction,

$\overline{\beta}_i$ is the effective fractional yield of the i th group of delayed neutrons,

Λ is the prompt neutron lifetime,

λ_i is the decay constant of the i th precursor group,

$C_i(t)$ is the concentration of the i th precursor group, and

I is the number of delayed neutron groups.

If these two equations are combined and if the extraneous source term is neglected the following equation for reactivity is obtained:

$$\rho(t) = \frac{\Lambda}{T(t)}\left[\frac{dT(t)}{dt} + \sum_{i=1}^{I}\frac{dC_i(t)}{dt}\right] \qquad (2.3.1\text{-}3)$$

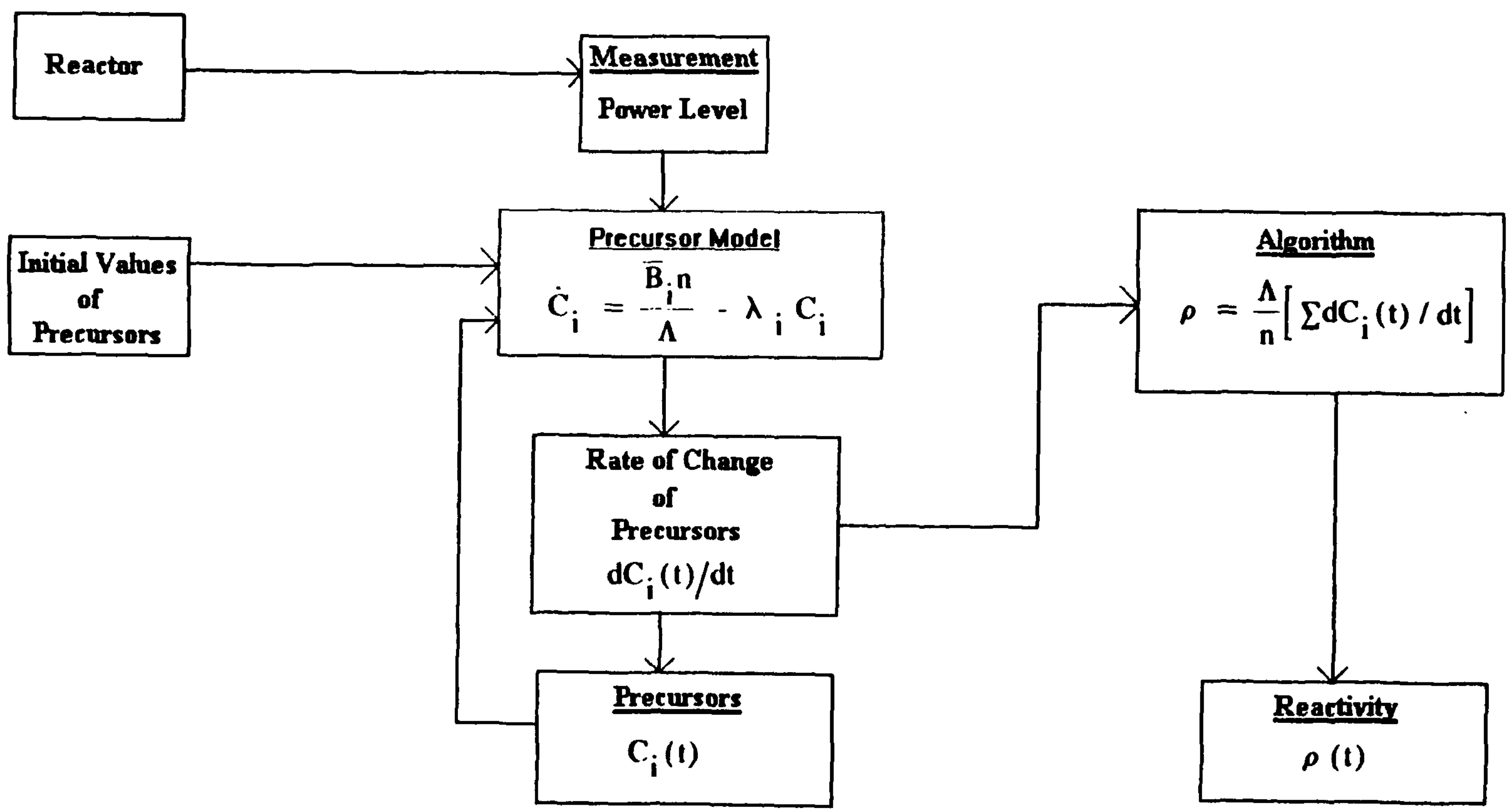
This method can be easily implemented through the direct measurement of reactor power. These measurements are then used to obtain the neutron amplitude function, $T(t)$,

which can then be used to estimate the precursor concentrations. The reactivity can then be determined. This implementation is displayed in Figure 2.3.1-1 [12].

2.3.2 Reactivity Balance Method

The reactivity balance method is easily implemented. Normally, it relies on identification of those reactor parameters that can have an effect on the reactor's effective neutron multiplication factor, Keff. These parameters may include fuel and moderator temperatures, control rod position, xenon concentration, and others. For each of these parameters, a reactivity coefficient is determined via experiment or theoretical calculation. A comparison of each parameter to its initial reference value is then made. This reference state is usually the condition that exist with the reactor critical at some steady-state power level. This allows a value of zero for the reactivity reference state.

Figure 2.3.1-1 Inverse Kinetics Reactivity Measurement Method



The net reactivity in the reactor for a deviation from the reference state can then be found by using the following relation [13]:

$$r(t) = \sum r_i(t) = \sum \left(\frac{dr}{dq}\right)_i dq_i(t) \qquad (2.3.2\text{-}1)$$

where: $\rho\ (t)$ is the net reactivity,

$\rho_i(t)$ is the reactivity due to the i th parameter,

$\left(\frac{\partial\rho}{\partial\theta}\right)_i$ is the reactivity coefficient for the i th parameter, and

$\partial\theta\ i\ (t)$ is the deviation of the i th reactor parameter from its reference value.

It should be noted that for reactor transients conducted over a short duration it is possible to neglect the effects of parameters that have very small reactivity addition rates. This would permit a simplified version of the reactivity balance involving the sum of the reactor thermal feedback reactivity effects and the reactivity associated with control rod movement.

This simplified reactivity balance can be implemented using the following relation:

$$\rho(t) = \frac{\delta\rho_{\text{rods}}}{\delta z}\delta z + \frac{\delta\rho_{\text{fuel}}}{\delta\bar{\theta}_f}\delta\bar{\theta}_f + \frac{\delta\rho_{\text{mod}}}{\delta\bar{\theta}_{\text{mod}}}\delta\bar{\theta}_{\text{mod}} \tag{2.3.2-2}$$

where: ∂z is the control rod travel from the reference position,

$\delta\bar{\theta}_f$ is the change in the average fuel temperature from the reference state,

$\partial\bar{\theta}$ mod is the change in the average moderator temperature from the reference state,

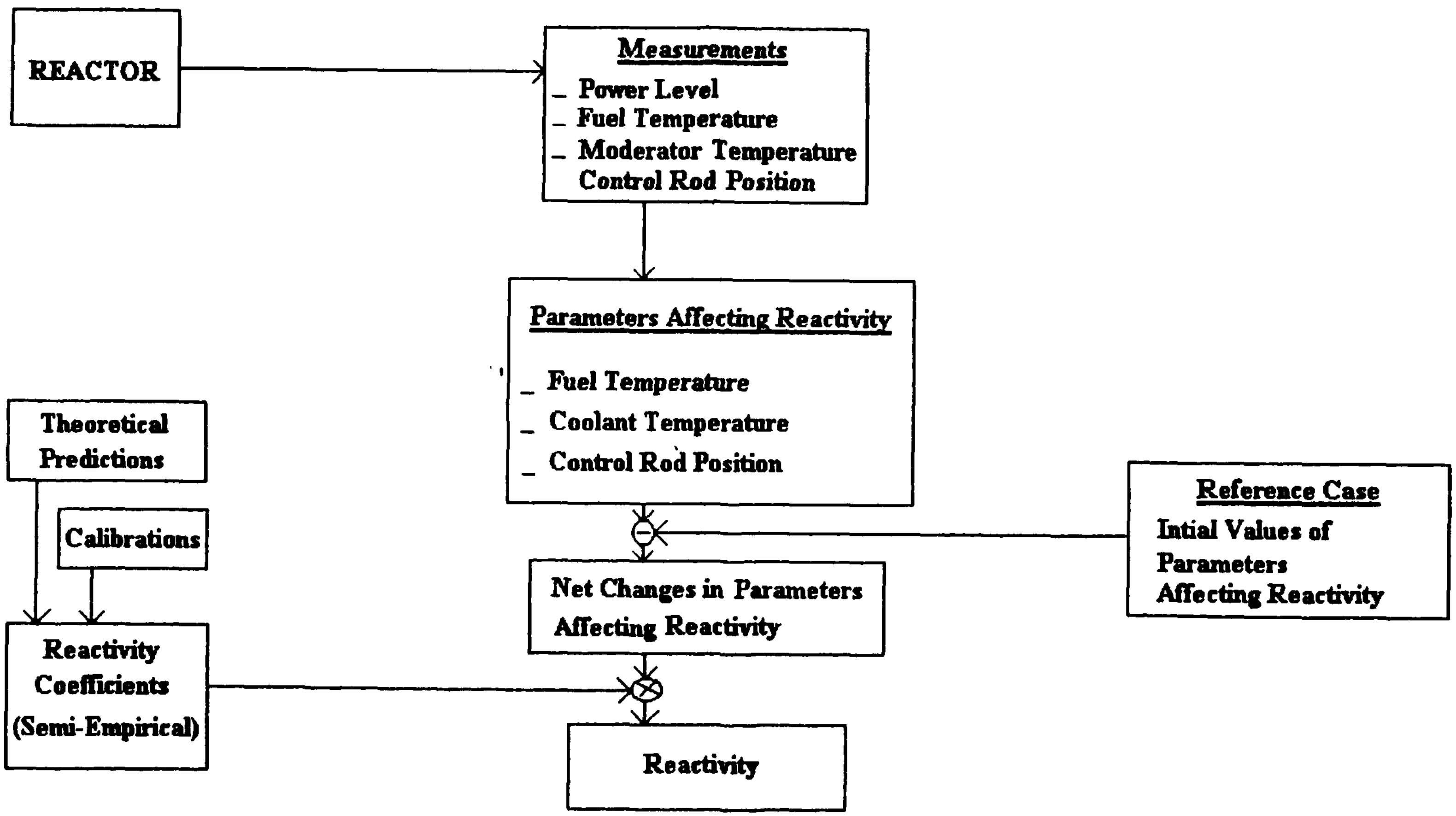
$\frac{\partial\rho \text{ rods}}{\partial z}$ is the differential control rod worth at a given position,

$\frac{\partial\rho \text{ fuel}}{\partial\bar{\theta}_f}$ is the fuel temperature coefficient of reactivity at a given temperature, and

$\frac{\partial\rho \text{ mod}}{\partial\bar{\theta}\text{mod}}$ is the moderator coefficient of reactivity.

This simplified reactivity measurement method is implemented by determining the differential rod worth for the controlling rod group and the thermal reactivity coefficients. The change in rod position, fuel temperature, and moderator temperature can be obtained either directly from reactor plant instrumentation or via calculations using analytical reactor models. This implementation is shown in Figure 2.3.2-1.

Figure 2.3.2-1 Simplified Reactivity Balance Method



2.3.3 Instrumented Synthesis Method

A third method for reactivity measurement is presently being investigated. This is the Instrumented Synthesis Method. This work is being pursued under the direction of Professor Allen F. Henry, Professor David Lanning, and Dr. John A. Bernard at MIT. The technique will employ continuous data from distributed in-core detectors to evaluate local core power distributions thereby allowing the global reactivity to be calculated [14]. The basic concept of the method is to estimate the instantaneous local neutron flux through the use of a linear combination of pre-computed, three-dimensional, static expansion-functions that bracket an expected reactor transient. The time-dependent coefficients of these functions are found by requiring the reconstructed neutron flux to agree with the locally obtained count rates from the in-core neutron detectors. If properly selected, these expansion-functions will account for variations in flux shape during transients. This leads to a potentially very accurate prediction of core power distribution and calculated global reactivity values without the spatial limitations of methods such as space-independent kinetics. A detailed explanation of this method is given by R. P. Jacqmin in the 1991 report "Combined Use Of In-Core Neutron Detectors and Precomputed, Three-Dimensional, Nodal Flux-Shapes Neutron Distribution In Light-Water Reactors" [15]. An excerpt from this paper is provided in Appendix E.

2.4 Chapter Summary

The net reactivity, the rate of change of reactivity, and the precursor distributions characterize the power response of a nuclear reactor. Values of these parameters are needed to implement automated reactor control methods. The three methods considered here for reactivity measurement are Inverse Kinetics, Reactivity Balances, and Instrumented Synthesis. The use of these three "independent" methods of reactivity measurements for reactivity signal validation is discussed in Chapter Six. Considered next are the thermal-hydraulic relations required to implement a reactivity balance model.

3. Thermal-Hydraulic Reactor Model

In order to implement a reactivity balance model of a nuclear reactor it is necessary to develop an analytic method for predicting changes in the temperatures of the reactor fuel and moderator. This chapter details the theoretical development of an energy deposition model of a nuclear reactor fuel and moderator.

3.1 Energy Deposition Model

The basis of the thermal-hydraulic reactor model is a heat deposition model of the reactor core. These heat balance equations are [16]:

$$\begin{bmatrix} \text{Rate of Heat} \\ \text{Energy Change} \\ \text{in the Fuel} \end{bmatrix} = \begin{bmatrix} \text{Rate of Energy} \\ \text{Deposition in the} \\ \text{Fuel From Fission} \end{bmatrix} - \begin{bmatrix} \text{Rate of} \\ \text{Heat Energy Loss} \\ \text{To Cooling Media} \end{bmatrix} \tag{3.1-1}$$

$$\begin{bmatrix} \text{Rate of} \\ \text{Heat Energy} \\ \text{Change for} \\ \text{Moderator} \\ \text{within the Core} \end{bmatrix} = \begin{bmatrix} \text{Rate of Heat} \\ \text{Energy Deposition} \\ \text{for Moderator within the Core} \\ \text{from Fission} \\ \text{(Gamma Heating)} \end{bmatrix} + \begin{bmatrix} \text{Rate of Heat} \\ \text{Energy Transfer} \\ \text{from Fuel to} \\ \text{Moderator} \\ \text{within the Core} \end{bmatrix} - \begin{bmatrix} \text{Rate at} \\ \text{which Heat} \\ \text{Energy is} \\ \text{Carried From} \\ \text{The Core} \\ \text{By Moderator} \end{bmatrix} \tag{3.1-2}$$

The individual blocks of these equations were developed by Professors Neil E. Todreas and Mujid S. Kazimi in their text "Nuclear Systems I - Thermal Hydraulic Fundamentals" [17]. They use a lumped parameter integral approach to develop a simplified set of equations for the fuel and moderator rate of energy change in terms of material temperatures. These equations use core-averaged parameters for the material thermodynamic properties as well as core-averaged material temperatures. The use of an average material temperature assumes a linearly-developed temperature profile within the material. These individual block relations are:

$$\begin{bmatrix} \text{Rate of Heat} \\ \text{Energy Change} \\ \text{in the Fuel} \end{bmatrix} = \rho_{fuel} V_{fuel} C_{p_{fuel}} \frac{\delta \bar{\theta}_{fuel}}{\delta t} \tag{3.1-3}$$

$$\begin{bmatrix} \text{Rate of Heat} \\ \text{Energy Change} \\ \text{in the Moderator} \end{bmatrix} = \rho_{mod} V_{mod} C_{p_{mod}} \frac{\delta \bar{\theta}_{mod}}{\delta t} \tag{3.1-4}$$

$$\begin{bmatrix} \text{Rate of Heat} \\ \text{Energy Deposition} \\ \text{in the Fuel From} \\ \text{Fission} \end{bmatrix} = (1 - \gamma)\omega \chi_{fuel} \Sigma_f \bar{\Phi} V_{fuel} \tag{3.1-5}$$

$$\begin{bmatrix} \text{Rate of Heat Energy} \\ \text{Deposition from Fission} \\ \text{in the Moderator } (\gamma \text{ heating}) \end{bmatrix} = \gamma \chi_{fuel} \Sigma_f \overline{\Phi} V_{fuel} \tag{3.1-6}$$

$$\begin{bmatrix} \text{Rate of Heat Transfer} \\ \text{Loss / Gain by} \\ \text{Fuel / Moderator} \end{bmatrix} = A_{fuel} h(\overline{\theta}_{fuel} - \overline{\theta}_{mod}) \tag{3.1-7}$$

$$\begin{bmatrix} \text{Net Rate of Energy Loss} \\ \text{by Moderator within the} \\ \text{Core via Moderator Flow} \end{bmatrix} = \dot{M} C_{p_{mod}} (\theta^{in}_{mod} - \theta^{out}_{mod}) \tag{3.1-8}$$

where: ρ_{mod} is the average moderator density,

ρ_{fuel} is the average lumped fuel material density,

$C_{p_{fuel}}$ is the average lumped fuel material heat capacity,

$C_{p_{fuel}}$ is the average moderator heat capacity,

A is the lumped fuel materials surface area,

h is the overall heat transfer coefficient for the fuel material to the coolant,

γ is the percent of thermal energy from fission deposited in the moderator via gamma heating,

χ_{fuel}	is the average lumped fuel recoverable energy per fission,
Σ_f	is the macroscopic cross section for fission,
$\overline{\Phi}$	is the average core one group neutron flux,
$\dot{M}$	is the mass flow rate of the coolant,
$\overline{\theta}_{fuel}$	is the average fuel temperature,
$\overline{\theta}_{mod}$	is the average core moderator temperature,
$\overline{\theta}_{mod}^{in}$	is the moderator inlet temperature, and
θ_{mod}^{out}	is the moderator outlet temperature which is defined as:

$$\overline{\theta}_{mod} \equiv \frac{\theta_{out}^{in} + \theta_{mod}^{out}}{2}$$

Equations 3.1-5 and 3.1-6 can be further simplified by assuming a constant flux shape, S(r,E), during transient operations. This implies that the neutron flux $\overline{\Phi}$ is proportional to the observed reactor power that is sensed via neutron leakage detection. Thus, within the limits of space independent kinetics, we can replace $\chi_f \Sigma_f \overline{\Phi} V_{fuel}$ with the observed reactor power, N(t). In the case of a pool type reactor, it would be advantageous to eliminate the θ_{mod}^{out} term. The moderator outlet temperature may be difficult to obtain accurately while the moderator inlet temperature or pool temperature

may be readily sensed. Re-writing equation 3.1-8 in terms of $\theta^{in}_{mod} = \theta pool$ and $\bar{\theta}\,mod$ yields the following:

$$\begin{bmatrix} \text{Net Rate of Heat Loss} \\ \text{by Moderator due to} \\ \text{Coolant Flow} \end{bmatrix} = 2\dot{M}C_{p_{mod}}(\bar{\theta}_{mod} - \theta_{pool}) \tag{3.1-9}$$

This relation assumes a fully developed coolant flow and a constant axial heat flux. The overall heat balance equations represented by 3.1-1 and 3.1-2 can now be written as follows:

$$\rho_{fuel} V_{fuel} C_{p_{fuel}} \frac{\delta \bar{\theta}_{fuel}}{\delta\ t} = (1-\gamma)N(t) - A_{fuel}h(\bar{\theta}_{fuel} - \bar{\theta}_{mod}) \tag{3.1-10}$$

$$\rho_{mod} V_{mod} C_{p_{mod}} \frac{\delta \bar{\theta}_{mod}}{\delta\ t} = \gamma N(t) + A_f h(\bar{\theta}_{fuel} - \bar{\theta}_{mod}) - 2\dot{M}C_{p_{mod}}(\bar{\theta}_{mod} - \theta_{pool}) \tag{3.1-11}$$

where: $N(t)$ is the observed reactor power, and

θ_{pool} is the sensed reactor pool temperature.

Applying these equations over a discrete time step, ∂t, allows the temperature at a future time (K+1) to be calculated from the present time (K) values of $\bar{\theta}_{fuel}$, n, $\bar{\theta}_{Mod}$, and θ_{pool}. These discrete time equations are:

$$\overline{\theta^{n+1}_{fuel}} = \overline{\theta^{n}_{fuel}} + \delta t\left[K_1(\bar{\theta}^{n}_{\mathrm{mod}} - \bar{\theta}^{n}_{\mathrm{fuel}}) + K_2 \mathrm{N}^n\right] \tag{3.1-12}$$

$$\overline{\theta^{n+1}_{\mathrm{mod}}} = \overline{\theta^{n}_{\mathrm{mod}}} + \delta t\left[K_3\left(\overline{\theta^{n}_{fuel}} - \overline{\theta^{n}_{\mathrm{mod}}}\right) + K_4 \mathrm{N}^n - K_5\left(\overline{\theta^{n}_{\mathrm{mod}}} - \theta^{n}_{pool}\right)\right] \tag{3.1-13}$$

where:

$$K_1 = \frac{A_f h}{\rho_{fuel} V_{fuel} C_{p\,fuel}}, \tag{3.1-14}$$

$$K_2 = \frac{(1-\gamma)}{\rho_{fuel} V_{fuel} C_{p\,fuel}}, \tag{3.1-15}$$

$$K_3 = \frac{A_f h}{\rho_{\mathrm{mod}} V_{\mathrm{mod}} C_{p_{\mathrm{mod}}}}, \tag{3.1-16}$$

$$K_4 = \frac{\gamma}{\rho_{mod} V_{mod} C_{p_{mod}}}, \text{ and} \tag{3.1-17}$$

$$K_5 = \frac{2\dot{M}}{\rho_{mod} V_{mod}}. \tag{3.1-18}$$

3.2 Model Limitations

These discrete time equations form a linear system model for fuel and moderator temperature prediction. This model assumes that the core-averaged lumped thermal parameters are constant with temperature. This is not an accurate assumption for transients that cause large temperature changes. For model accuracy, it is necessary to ensure that the thermal parameters are properly modeled as functions of either moderator or fuel temperature.

The temperature dependence of the core thermal parameters causes the thermal-hydraulic model of the reactor to become non-linear. This non-linearity complicates the estimation of model parameters for use in model adaptation or self alignment. A method for achieving model adaptation or self alignment is discussed in Chapter Four.

The energy deposition model also relies on the previously stated assumptions of:

- Constant flux shape
- Linearly developed temperature profiles
- Fully-developed constant flow
- Constant radial heat flux

Prior to model implementation, for a given reactor design, it is necessary to verify the accuracy of the models integral lumped parameter approach. The comparison of this energy deposition model to a discrete finite element system model is performed in Chapter Five.

3.3 Chapter Summary

In this chapter a generic energy deposition model of a reactor core has been developed. This model is capable of tracking fuel and moderator temperatures during reactor operations. The model uses lumped, integral, core-averaged thermal-hydraulic parameters and assumes a linear, fully-developed, temperature distribution throughout the fuel and moderator. While generically developed, the final relationship, equations 3.1 -12 and 3.1-13, are specially tailored for the modeling of a pool type reactor. Model inputs include the initial moderator temperature ($\overline{\theta_{\text{mod}}}$), initial fuel temperature (θ_{fuel}), reactor power (N), and reactor pool temperature (θ_{pool}) at discrete time intervals. The model is linear for constant thermal-hydraulic parameters and provides a suitable basis for use with model-adaptive or self-aligning routines. However, the temperature dependence of the thermal-hydraulic parameters in the model required to operate over an extensive

temperature range introduces a non-linearity which greatly effects the method of model adaptation. The following chapter examines a method of adaptive self-alignment for a non-linear system model.

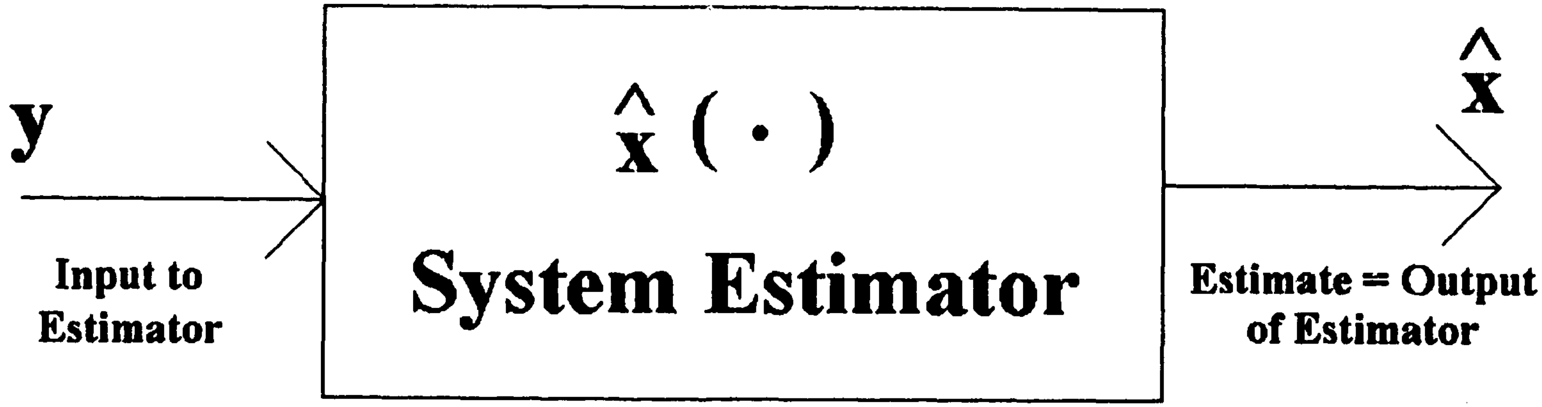
4 Reactivity Model Adaptive Routine and Parameter Estimation

In Chapters Two and Three, models were derived for predicting reactor fuel and moderator temperatures as well as reactivity. These models were based on energy deposition relations that use integral, lumped, core-averaged thermal-hydraulic parameters coupled with a reactivity balance model. These model parameters were a function of the material's temperature. Values for these parameters are obtained either by theoretical calculation or through experimentation on the reactor being modeled. During reactor operation, the actual values of these parameters could vary slightly from those originally obtained. Should this occur, it would be advantageous to allow the model to adapt to these parameter changes. This chapter details a method for model adaptation by use of minimum variance estimation in the form of an extended Kalman Filter.

4.1 Minimum Variance Estimation

We can develop a system estimation scheme in terms of system parameters, X, and system outputs, Y. Such an analysis is described in "Optimal Filtering" by Brian D. Anderson and John Moore [18]. A possible estimation scheme is shown in Figure 4.1-1. As an example, we might examine a solution of form $Y = AX = a_1x_1 + \bullet \bullet \bullet + a_nx_n$ where A is an m x n matrix and X is the state vector. We can define any error inherent in this system by an error term (e) where $e = Y - AX$. As an estimator of x we could choose the criteria to minimize the variance of the square error. (i.e. $\min_x \sum e_i^2$). This type of estimation is known as a "Least Square Error" estimation.

Figure 4.1-1 Standard System Estimator



The solution [19] to this minimization is easily shown to be :

$$\hat{X} = (A^T A)^{-1} A^T y \tag{4.1-1}$$

This result lends itself to recursive parameters estimation. One such type of method is Kalman Filtering or Kalman Estimation.

4.2 Kalman Estimation

The Kalman Estimation technique can be applied on a discrete system such as the following:

$$X_{k+1} = F_k X_k + G_k W_k \tag{4.2-1}$$

$$z_k = H_k^T X_k + v_k \tag{4.2-2}$$

where:	k	is the discrete time step,
	X	is the system state,
	Z	is the system output,
	V_k, W_k	are the white noise signals, and
	F_k, G_k, H_k	are the system descriptive matrices.

The recursive equations for estimating the system state are derived as follows [20].

$$\hat{X}_{k/k} = \hat{X}_{k/k-1} + \Sigma_{k/k-1} H_k (H_k^T \Sigma_{k/k-1} H_k + R_k)^{-1} (Z_k - H_k^T \hat{X}_{k/k-1}) \tag{4.2-3}$$

$$\Sigma_{k/k} = \Sigma_{k/k-1} - \Sigma_{k/k-1} H_k (H_k^T \Sigma_{k/k-1} H_k + R_k)^{-1} H_k^T \Sigma_{k/k-1} \tag{4.2-4}$$

$$\hat{X} = \left[F_k - K_k H_k^T\right] \hat{X}_{k/k-1} + K_k Z_k \tag{4.2-5}$$

$$\Sigma_{k/k-1} = F_k\left[\Sigma_{k/k-1} - \Sigma_{k/k-1} H_k \left(H_k^T \Sigma_{k/k-1} H_k + R_k\right)^{-1} H_k^T \Sigma_{k/k-1}\right] F_k^T + G Q_k G_k^T \tag{4.2-6}$$

$$K_k = F_k \Sigma_{k/k-1} H_k \left[H_k^T \Sigma_{k/k-1} H_k + R_k\right]^{-1} \tag{4.2-7}$$

$$Q_k = \sum_0^k F_i^T F_i = P_k^{-1} \tag{4.2-8}$$

where: Σ_k is the error covariance matrix,

P_k is the state covariance matrix,

Q_k is the reciprocal of the state covariance matrix,

K_k is the Kalman gain matrix,

R_k is the noise covariance matrix,

k/k is the solution at time k calculated with k known values,

k+1/k is the solution at time k+1 calculated with k known values, and

k/k-1 is the solution at time k calculated with k-1 known values.

The Kalman estimator can be initialized by selecting $\Sigma_{0/-1} = P_o = (Fo^TFo)^{-1}$. Equations 4.2-3, and 4.2-4 can be viewed as the estimator equations. They determine the best estimate of the state, x, and the difference or error covariance, Σ_k. These estimates are based on current system parameters and the previously estimated state and covariance values. Equations 4.2-5 and 4.2-6 are used to propagate the solution forward. This provides a means of continuously updating a system's state by means of the Kalman estimator routine. It should be noted that the estimator tends to become "saturated" after numerous samples. This could lead to a change in the system's state not being detected. This difficulty can be overcome by periodically reinitializing the Kalman estimator. This type of estimation arrangement is often termed a state observer because the model's state

is estimated based on the difference between the model output and the actual system output.

For linear systems, this estimation routine, produces an "optimum" estimation or arrival trajectory to the desired state. The calculations are greatly complicated if the system of equations under consideration is not linear. To estimate the state of a non-linear system model it is necessary to extend the Kalman estimator routine to handle the non-linearity.

4.3 The Extended Kalman Estimator

To use the Kalman estimator for linear systems on a non-linear system model we must first linearize the system equations. The system equations are now given as:

$$X_{k+1} = f_k (X_k) + g_k (X_k) w_k \tag{4.3-1}$$

$$Z_k = h_k (X_k) + v_k \tag{4.3-2}$$

These system equations are very similar to those of the linear system model given in equations 4.2-1 and 4.2-2 except that the system matrices are now non-linear functions of the systems state. To linearize these equations, a first order Taylor Series Expansion is used [21].

For this method, the following partial derivatives are used:

$$F_k = \left.\frac{\delta f_k}{\delta x}\right|_{x = \hat{x}_{k/k}} \tag{4.3-3}$$

$$H_k^T = \left.\frac{\delta h_k(x)}{\delta x}\right|_{x = \hat{x}_{k/k}} \tag{4.3-4}$$

$$G_k = g_k(\hat{x}_{k/k}) \tag{4.3-5}$$

Thus, neglecting higher order terms, the new linearized system of equations becomes:

$$X_{k+1} = F_k X_k + G_k w_k + u_k \tag{4.3-6}$$

$$Z_k = H_k^T X_k + v_k + y_k \tag{4.3-7}$$

with u_k and y_k as error signals given by:

$$u_k = f_k(\hat{x}_{k/k}) - F_k \hat{x}_{k/k} \tag{4.3-8}$$

$$y_k = h_k(\hat{x}_{k/k}) - H_k^T \hat{x}_{k/k-1} \tag{4.3-9}$$

Given these linearized system equations, the estimator equations for the Extended Kalman estimator can be written. These equations are:

$$\hat{x}_{k/k} = \hat{x}_{k/k-1} + L_k\left[z_k - h_k(\hat{x}_{k/k-1})\right] \tag{4.3-10}$$

$$\hat{x}_{k+1/k} = f_k(\hat{x}_{k/k}) \tag{4.3-11}$$

$$L_k = \Sigma^{*}_{k/k-1} H_k \Omega_k^{-1} \tag{4.3-12}$$

$$\Omega_k = H_k^T \Sigma_{k/k-1} H_k + R_k \tag{4.3-13}$$

$$\Sigma_{k/k} = \Sigma_{k/k-1} - \Sigma_{k/k-1} H_k [H_k^T \Sigma_{k/k-1} H_k [H_k^t \Sigma_{k/k-1} H_k + R_k]^{-1} H_k^T \Sigma_{k/k-1} \tag{4.3-14}$$

$$\Sigma_{k+1/k} = F_k \Sigma_k F_k^T + G_k Q_k G_k^T \tag{4.3-15}$$

The above extended Kalman estimator uses an estimator gain, L_k, calculated in a manner similar to the standard Kalman estimator gain, K_k. The estimator functions in the same manner as the standard Kalman estimator with a single exception. Specifically, because of the system non-linearity, the trajectory to the desired system state can no longer be guaranteed optimal. Variations of this extended Kalman estimator using the higher order terms of the taylor series expansion may improve the estimator trajectory at the cost of using longer, more involved estimation calculations.

4.4 Reactivity Model Adaptation Equation Development

The method of state estimation using an extended Kalman estimator can be applied to the reactivity balance model developed in Chapters Two and Three to achieve model adaptation to varying system parameters. The state equation for the reactivity balance model can be written as follows:

$$x(k+1) = \begin{bmatrix} T_f(k+1) \\ a(k+1) \\ b(k+1) \\ c(k+1) \end{bmatrix} = \begin{bmatrix} f_k(T_{f_k}, a_k, b_k, c_k) \\ a_k \\ b_k \\ c_k \end{bmatrix} \tag{4.4-1}$$

$$\text{reactivity} = h_k(X_k) + v_k$$

The system's state variables are the fuel temperature and the system thermal-hydraulic parameters appearing in the prediction equation for the fuel tempeature. Using the technique outlined in the previous section, we can write the linearized equations as:

$$\dot{x}(k+1) = F_k x_k + e_1 \tag{4.4-2}$$

$$\text{reactivity} = H_k^T x_k + e_2 \tag{4.4-3}$$

where e_1 and e_2 are a combination of system noise and system modeling errors. The equations for the extended Kalman estimator can now be directly applied. The individual entries in the linearized system matrices H_k, and F_k will be the partial derivatives of the system model equations taken with respect to the fuel temperature and the thermal-hydraulic parameters being estimated. In the case of F_k this is:

$$F_k = \begin{bmatrix} \frac{\delta f_k}{\delta T_f} & \frac{\delta f_k}{\delta a} & \frac{\delta f_k}{\delta b} & \frac{\delta f_k}{\delta c} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.4-4}$$

The noise covariance term, R_k, in equation 4.3-14 is not known for this application. This parameter can be reserved as a tuning parameter for the Extended Kalman estimator. A variety of simulations can be run using various values of R_k to

determine which value allows the adaptive routine to best estimate the system parameters while still providing robust estimator operation.

4.5 Chapter Summary

A method for achieving model adaptation as a means for providing model error correction by means of Extended Kalman estimation has been examined. The Extended Kalman estimation routine provides for linearizing a system model by means of a Taylor Series Expansion. The linearized model provides a system of equations for state identification. The system state consists of the Reactivity Balance Model's fuel temperature as well as specified thermal-hydraulic parameter coefficients that may vary during reactor operation. The Extended Kalman estimator routine provides a means for estimating the best values of the system parameters needed to minimize the reactivity error between the modeled system reactivity and a provided reactivity signal of the reactor system.

5. Verification of the Adaptive Reactor Reactivity Model

An adaptive reactor reactivity balance model can be constructed from the methods described in Chapters Two, Three, and Four. This chapter examines the construction of this model for the Annular Core Research Reactor at Sandia National Laboratories in New Mexico. Verification of the methods of the preceding chapters is accomplished through simulations using various computer mathematical software.

5.1 Parameter Selection

To employ the equations developed in Chapters Two, Three, and Four, a variety of reactor thermal-hydraulic and neutronic parameters were required. Many of the reactor parameters were obtained from a copy of Chapter Four (Reactor Design) of the Annular Core Research Reactor (ACRR) Safety Analysis Report (SAR) [22]. This copy, which is currently under revision, was obtained courtesy of Mr. F. Mitch McCrory of the Reactor Applications Department at Sandia National Laboratories in Albuquerque, New Mexico. In addition to the SAR reactor design data, various thermal-hydraulic parameters of reactor materials were obtained from material reference handbooks, such as "The Metals Reference Handbook" [23], "The Handbook of Applied Thermal Design" [24], "Thermophysical Properties of Liquids and Gases" [25], and "Nuclear Systems I" [26]. Thermal-Hydraulic parameters that vary with temperature were calculated as polynomial functions instead of using tabular data. This was done to facilitate the partial derivatives necessary for implementing model adaptation via the Extended Kalman estimation. The fuel cell dimensions and core geometry needed for calculations were also obtained from Chapter Four of the ACRR's SAR.

5.1.1 Overall Heat Transfer Coefficient

The overall heat transfer coefficient of the fuel as a function of fuel temperature and the coolant mass flow rate as a function of moderator temperature were obtained from the reactor data provided in Chapter Four of the ACRR's SAR. Table 4.3-7 of the SAR provided equilibrium power, temperature, and flow conditions calculated for the ACRR [27]. These equilibrium conditions were benchmarked to four megawatts via reactor testing. The data from the SAR is provided here in Table 5.1.1-1. The table data assumes a constant inlet coolant temperature of 20°C. The overall heat transfer coefficient, h (watts/m^2), was calculated at each equilibrium temperature using the following relation:

$$h = \frac{P}{236\left[T_f^{ave} - \left[\frac{T_m^{exit} + 20}{2}\right]\right]0.59799} \qquad (5.1.1\text{-}1)$$

where:

	P	is the reactor power (Watts),
	T_f^{ave}	is the average fuel temperature (° C),
	T_m^{exit}	is the moderator exit temperature (° C),
	236	is the number fuel cells in ACRR,
	20	is the moderator inlet temperature (° C), and

0.059799 is the heat transfer surface area of a single fuel cell (m^2).

A polynomial relation between the calculated data points was obtained using Microsoft Excel, a standard PC software package. This polynomial relationship is given by the following equation:

$$h = 65.021 + 0.4438T_f + 2.6x10^{-4}T_f^2 + 7.6x10^{-8}T_f^3 \qquad (5.1.1\text{-}2)$$

5.1.2 Reactivity Feedback Coefficient

Chapter Four of the ACRR's SAR gives individual fuel and moderator reactivity feedback contribution equations [28]. Additional conversations with Mr. F. Mitch McCrory at Sandia National Laboratories indicated that an alternate equation had been calculated that gave a combined thermal feedback reactivity coefficient in terms of average fuel temperature.

Table 5.1.1-1

ACRR Calculated Equilibrium Relations

POWER	T_{fuel}^{ave} (°C)	T_{fuel}^{max} (°C)	$T_{clad}^{surface}$ (°C)	$T_{coolant}^{exit}$ (°C)	$\dot{M}$ (gal/s/rod)
1 W	20.1	20.1	20.1	20.1	0.26
1 kW	21.2	28.6	20.7	20.6	2.5
10 kW	26.7	36.5	23.1	21.6	5.4
100 kW	78.9	110.7	40.9	26.8	14.8
500 kW	244.4	347.0	82.2	38.1	28.8
1 MW	392.8	560.3	114.8	47.3	38.4
2 MW	607.8	874.8	118.7	61.8	49.8
3 MW	789.9	1146.2	118.7	73.2	59.1
4 MW	955.0	1400.0	118.6	83.0	66.8
5 MW	1089.4	1611.9	118.6	90.7	72.8
6 MW	1233.9	1844.1	118.5	98.6	78.9
7 MW	1371.1	2069.6	118.5	105.9	84.5
8 MW	1501.2	2284.2	118.5	112.8	89.6

This relationship had been shown by ACRR tests to provide good results for reactivity feedback calculations [29]. This equation is:

$$\frac{\delta\rho_{\mathit{feedback}}}{\delta\bar{\theta}_{f}} = \left(-3.85 - \left[\frac{730}{273+\bar{\theta}_{f}}\right]\right)\frac{10^{-5}}{0.0073} \qquad (5.1.2\text{-}1)$$

where the reactivity coefficient is in dollars of reactivity per degree centigrade. This relation is used to determine the thermal feedback reactivity in the Reactivity Balance Model.

5.2 Thermal-Hydraulic Model Verification

The heat deposition model derived in Chapter Three used core-averaged parameters to predict the average fuel and moderator temperatures. It was necessary to determine if the lumped-parameter approach using average temperatures could accurately model the core for both rapid and slow transients. A comparison of the lumped-parameter model response to that of a nodal heat transfer code was made. The lumped-parameter heat deposition model as developed in Chapter Three was simulated using MATHCAD, a PC based mathematical code. The nodal, finite element modeling was performed using

HEATING 5, an Oak Ridge National Laboratory, finite element, heat transfer PC code [31].

5.2.1 Thermal Model Testing using MATHCAD

A simplified version of the heat deposition equation was used to determine the average fuel temperature at individual time steps. This equation was:

$$\bar{\theta}_f^{k+1} = \bar{\theta}_f^{k} + \Delta t\left[\frac{\bar{\theta}_{\mathrm{mod}}^{k} h(\bar{\theta}_f^{k}) A + (1-\gamma)P^k - \bar{\theta}_f^{k} A h(\bar{\theta}_f^{k})}{\rho V C_{p_f}(\bar{\theta}_f^{k})}\right] \qquad (5.2\text{-}1)$$

where:

$\overline{\theta_f}$	is the average fuel temperature,
$\overline{\theta_{\mathrm{mod}}}$	is the average moderator temperature,
$h(\overline{\theta_f})$	is the overall heat transfer coefficient of the fuel to the moderator as a function of fuel temperature,
A	is the fuel heat transfer surface area,
P	is the reactor power,
ρ	is the average lumped fuel density,
V	is the average lumped fuel volume,

C_{p_f} is the average lumped fuel heat capacity, and

Δt is the duration of one time step.

Two types of transients were simulated. The first was a ramp power change from 100 kW to two megawatts over an interval of ten seconds. Fuel temperature was allowed to rise to new equilibrium conditions over a time of twelve minutes. The moderator temperature for this transient was simulated using steady-state equilibrium values obtained from Table 5.1.1-1. The second transient was a rapid power spike. Power was simulated to rise from one watt to 6400 MW in thirteen milliseconds. Power was then simulated to return to one watt over thirteen milliseconds. This produced a 6400 MW power spike with a half power width of approximately thirteen milliseconds. Moderator temperature, during this rapid power transient, was simulated constant at 20°C. Sample MATHCAD input files as well as fuel temperature plots are provided in Appendix A.

5.2.2 Model Comparison Using Heating 5

The nodal heat transfer code used for temperature response comparison was HEATING 5, which is a finite-element code developed by Oak Ridge National Laboratory. The PC version is capable of simulating 400 separate nodes. It can simulate various materials and allow heat transfer by convection, conduction, and radiation. The simulation involved constructing an input file to model an average core fuel cell [30]. Fuel cell geometry was specified using the material, geometry, and dimensions for the ACRR fuel cells as described in the ACRR's SAR Chapter Four [31]. The energy deposition in the fuel cell was peaked radially as described in the ACRR SAR Chapter Four [32]. The first transient simulated was a power ramp from 100 kW to two megawatts over a period

of ten seconds. Temperatures were allowed to rise to their new equilibrium values as in the MATHCAD simulation. The moderator temperature was modeled using the method described for the MATHCAD simulation. The second transient was a 6400 MW power spike with a half power pulse width of thirteen milliseconds. The moderator temperature was simulated as constant at 20°C. Sample HEATING 5 input and output files for these transients are shown in Appendix B.

5.2.3 Discussion of Results

The output files from the HEATING 5 analysis were used to calculate average fuel temperatures at each data time step. This average temperature response of the fuel is shown in Figures 5.2.3-1 and 5.2.3-2. These results show very similar responses for the two models under both types of the examined transients. The maximum deviation between the two models was 1.77% during the rapid transient and 1.85% during the slow transient.

The temperature profile across the fuel cell during the rapid transient was also examined. The Heating 5 fuel temperature profile at various time steps is shown in Figure 5.2.3-3. This profile shows that a linear temperature profile exists even during very rapid transients. Also, the high degree of isolation between the fuel and cladding provide the thermal profile necessary to allow the use of an average fuel temperature for heat transfer calculations.

Figure 5.2.3-1 Fuel Temperature Response - Slow Transient

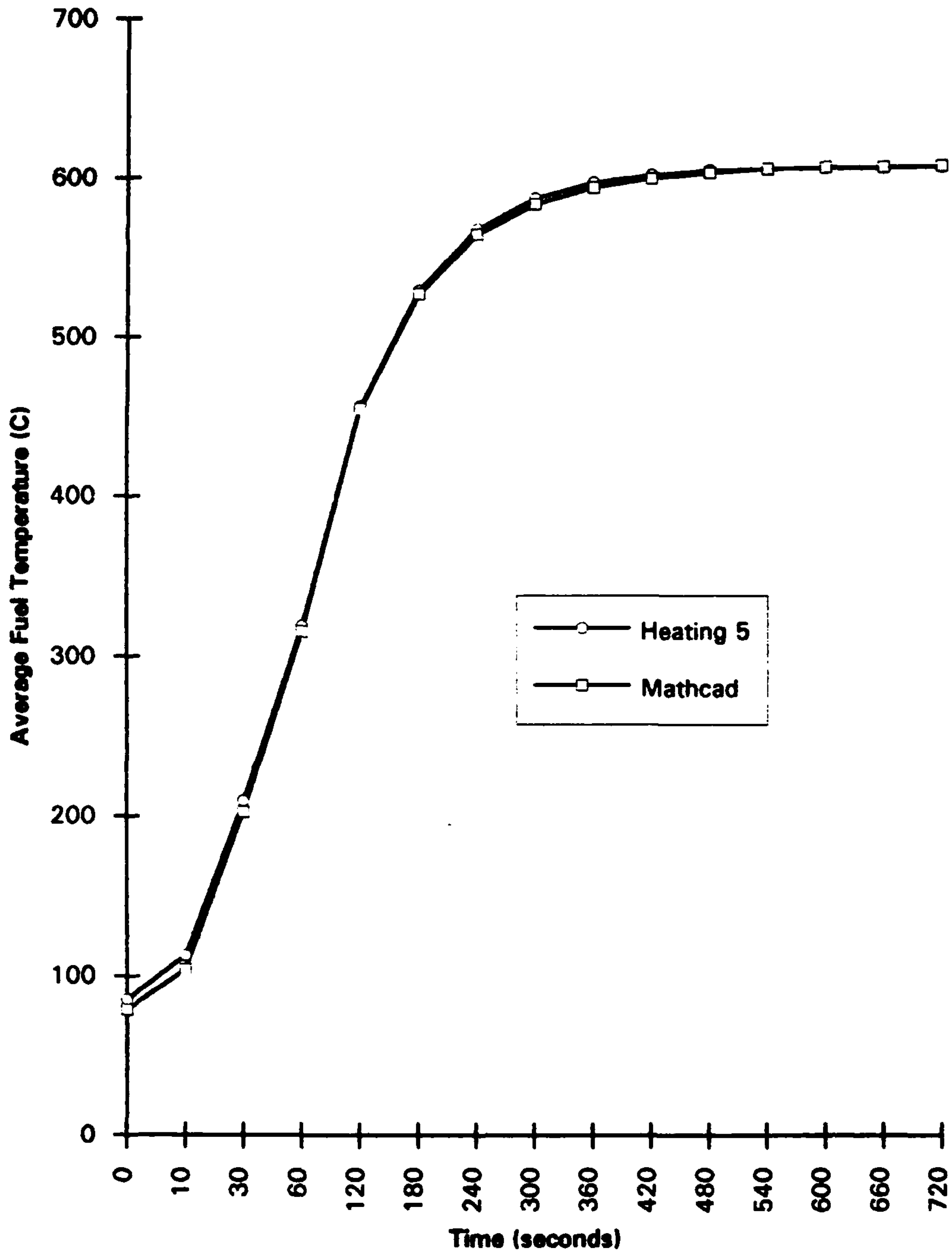


Figure 5.2.3-2 Fuel Temperature Response - Rapid Transient

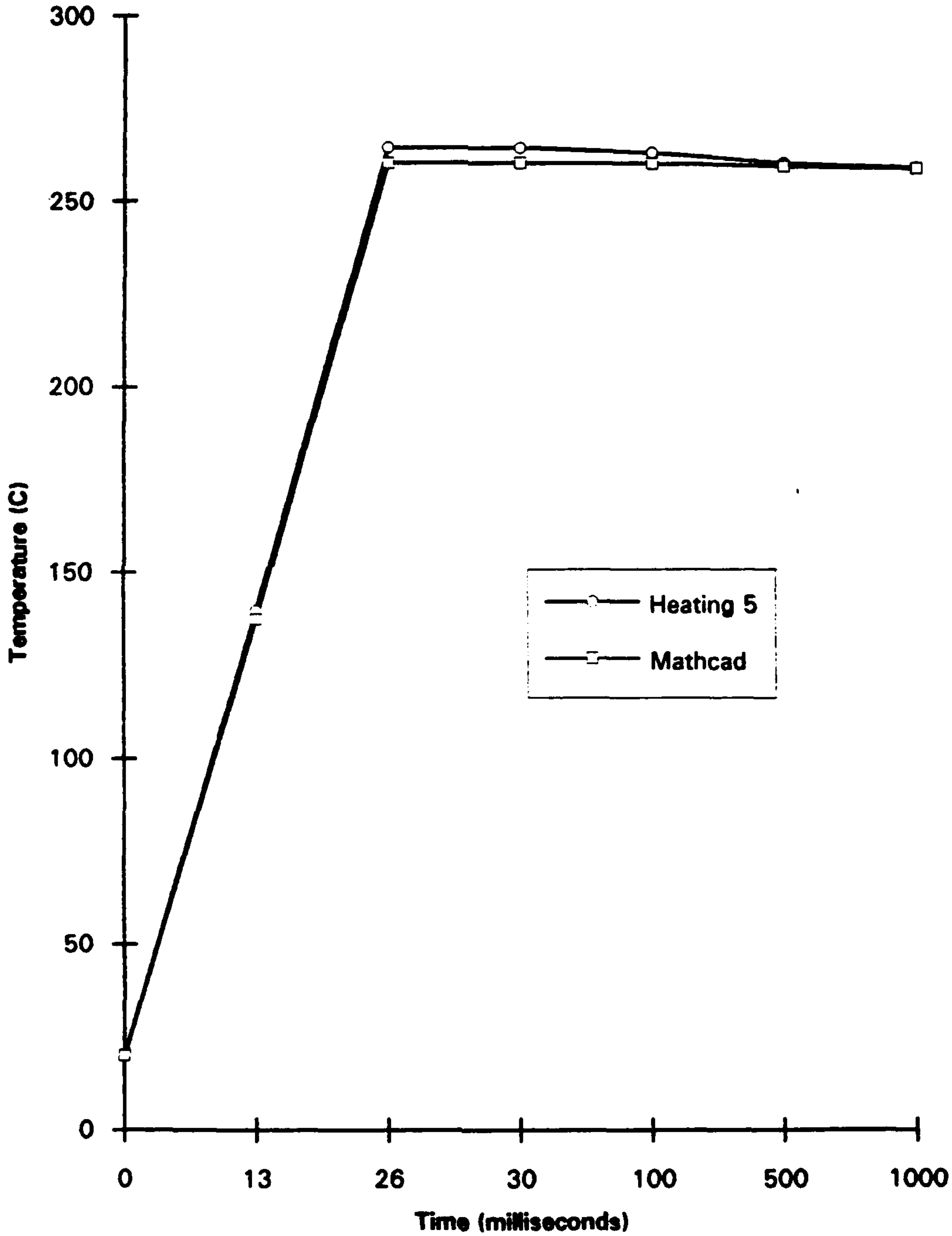
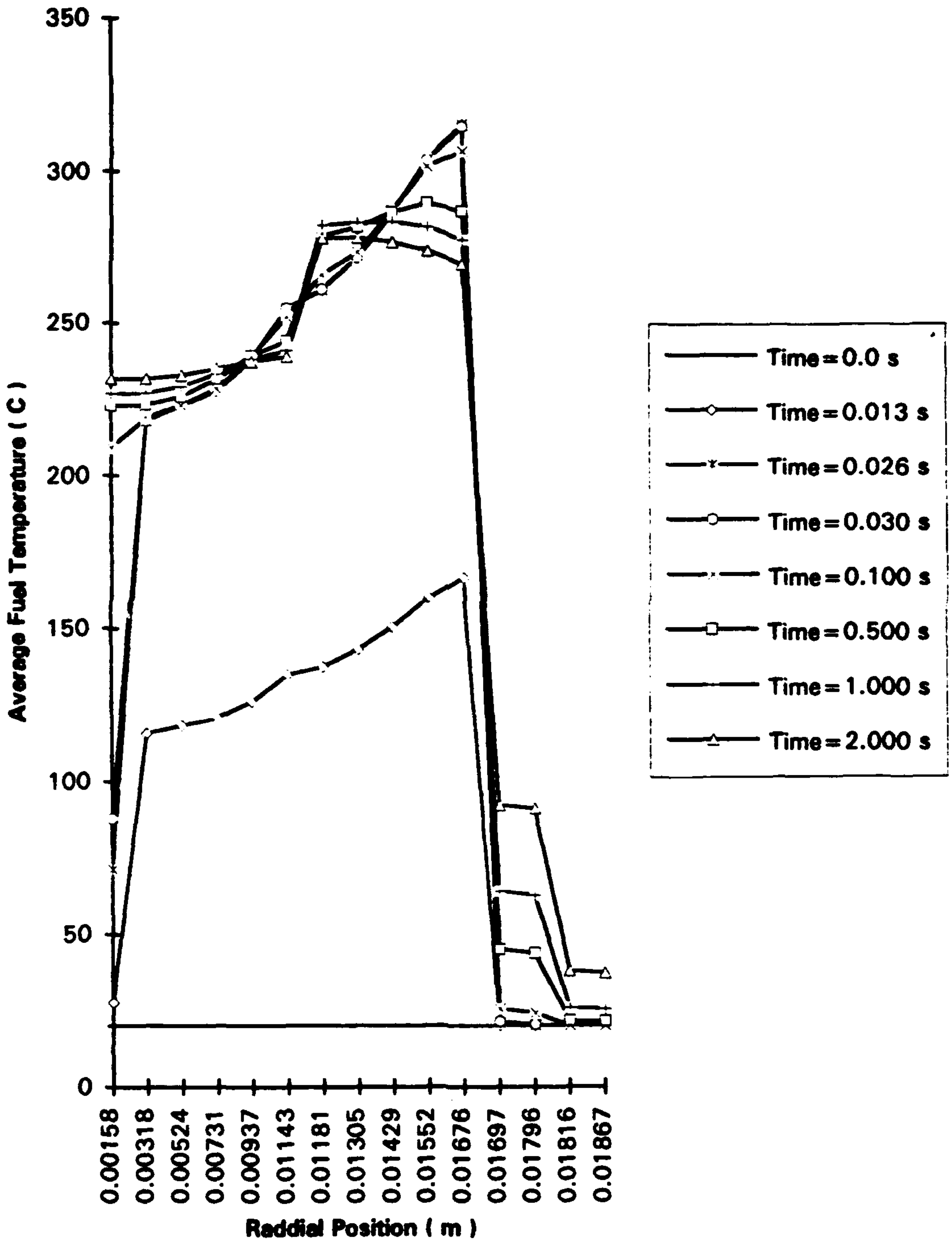


Figure 5.2.3-3 Fuel Temperature - Radial Distribution



5.3 Adaptive Estimation Technique Assessment

Section 5.2 established the proper operation of the heat deposition model for temperature prediction in the ACRR fuel. The operation of the Kalman Estimation Technique presented in Chapter Four is examined in this section. The PC-based software MATLAB was chosen for this assessment because it readily handled the matrix mathematics required for the Kalman estimation implementation. The simulation involved a power transient from three kW to four MW over a five second time interval. Power was then held level at four MW for the duration of the transient.

5.3.1 MATLAB Simulation for ACRR Model

The heat deposition model of Chapter Three was implemented using equations 3.1-12, and 3.1-13. The thermal-hydraulic properties were developed as second order polynomials to allow for obtaining the partial derivatives required for model linearization. A data list of input power and associated feedback reactivity was obtained by running the heat deposition model with an appropriate power signal. Two separate input reactivity files were generated. The first was the calculated reactivity as generated by the analytic model. The second file contained the calculated reactivity values with a two percent random noise signal added. These two files were used to simulate system reactivity inputs to the adaptive Kalman Estimator routine and there-by to establish the effects of signal noise on estimator performance. Copies of these MATLAB input files are provided in Appendix C.

The Kalman estimator was implemented using the equations developed in Chapter Four. Three key thermal-hydraulic parameters were chosen for adaptation. These parameters were the first-order coefficient of the heat capacity, and the first and second order terms of the overall heat transfer coefficient. Selection of these specific terms provides adjustable coefficients for the power, fuel temperature, and the squared fuel temperature in the heat deposition model. If these model coefficients are set to zero, there is essentially no heat transfer in or out of the fuel. This allows the Kalman estimator to derive the best values for the coefficients that "fit" the system's reactivity input signal. To reduce the effects of system noise on the estimated thermal-hydraulic parameters, a weighted-average smoothing-function was used. This output smoothing allows the Kalman estimator to use higher values of gain needed to develop system thermal-hydraulic parameters rapidly. This smoothed signal could be used to assess the "steadiness" of the estimated values. The estimation routine employs the following algorithm:

1. Initialize estimator parameters.

2. Obtain values of system inputs: Power, reactivity, and pool temperature.

3. Obtain current values of model parameters:

    - Reactivity
    - Fuel temperature
    - Moderator temperature
    - Selected thermal-hydraulic coefficients for estimation.

4. Calculate the Kalman Estimator Gain.

5. Estimate the "best" values of model reactivity, fuel temperature, thermal-hydraulic parameters to fit system inputs.

6. Update model with estimated parameters.

7. Repeat steps two through six until the smoothed estimated values of the model thermal-hydraulic parameters no longer change with each iteration.

Sample MATLAB input files showing this implementation are provided in Appendix C.

5.3.2 Discussion of MATLAB Simulation Results

The initial simulation run involved input reactivity values with no noise. The Kalman estimator attempted to derive the best values for reactivity and thermal-hydraulic parameters based on system input reactivity. The degree of estimator success was judged by how closely the estimator could determine the original thermal-hydraulic parameters used to develop the system input reactivity. A value of 10^{-15} was chosen for the noise covariance, R, for the initial run. The sample interval was set at 50 milliseconds. The MATLAB output charts for this transient are provided in Appendix C. The estimator was extremely accurate in determining the system thermal-hydraulic parameters. After 50 samples, the estimator had determined the system thermal-hydraulic parameters to within 0.01 percent.

A simulation with system input noise set at two percent and R set at 10^{-15} produced very poor results. The estimator was not able to determine the system thermal-hydraulic parameters. This estimator divergence was determined to be the result of an excessive Kalman gain for the input noise level simulated. To reduce the Kalman gain, the chosen value of R was set to 10^{-7}.

A simulation with system input noise set at two percent and R set at 10^{-7} produced a successful estimation run. It was noted that, with the reduced gain, the estimator took much longer to determine the system thermal-hydraulic parameters than in the no-noise high-gain run. After approximately 400 samples (20 seconds) the estimator had determined the system thermal-hydraulic parameters to within 6.18 percent. After approximately 1300 samples (65 seconds) the estimator had determined system thermal-hydraulic parameters to within 2.2 percent. Estimator accuracy continued at approximately two percent through the duration of the simulation. The data generation scheme was re-run using the estimation values obtained during the simulation. The generated reactivity using these estimated values fell within the 2% envelope of the initially calculated reactivity data. The MATLAB output charts for this simulation are provided in Appendix C.

These simulations show that the estimator routine can accurately determine the system operating characteristics based solely upon the system input reactivity. The speed at which the estimator arrives at a stable solution is determined by both the amount of system input noise and the selected value of the noise covariance. The noise covariance, R, should be choose to provide the "optimum" solution. Excessively small values of R

lead to excessive Kalman estimator gain and divergence of estimated values. Excessively large values of R lead to longer solution times.

5.4 Chapter Summary

The verification of the adaptive reactor reactivity model was accomplished by means of simulations using a variety of PC-based heat transfer and mathematical software. A comparison of the heat deposition model of the ACRR, simulated in MATHCAD, was made against a thermal-hydraulic simulation of an average ACRR fuel rod using Heating 5. The simulations showed that the heat deposition model of the ACRR using average temperatures and integral, lumped, average core thermal-hydraulic parameters could accurately predict core fuel temperature. Simulation of the adaptive routine using a Kalman estimator were performed using MATLAB. The estimator determined system thermal-hydraulic operating characteristics to within two percent of their actual values when run using a system reactivity signal with two percent noise. Estimator speed for solution determination was found to be dependent on the input system noise as well as on the selected estimator gain. Model operation with estimated values of thermal-hydraulic parameters accurately approximated system operation within the limits of simulated noise.

6. Validation of Reactivity Input Signals

The successful operation of a complex system is dependent upon the validity of the sensor signals that are use to provide information for control. The use of validated control inputs serves to enhance controller performance. Validation can be accomplished through signal averaging which minimizes the effects of signal noise and isolation which eliminates the effects of faulty sensors. The parity space approach uses redundant sensors to accomplish fault detection and isolation and thereby provide validated signal inputs for a control system.

6.1 The Parity Space Approach

The fault detection process can be divided into two stages. These are residual generation and decision making. The redundant measurements of a process variable can be modeled by a measurement equation as [33]:

$$m = Hx + e \tag{6.1-1}$$

where m is the $(\ell \times 1)$ vector of measurements that are generated from ℓ sensors, H is the measurement matrix of dimension $(\ell \times n)$ and rank n, and x is the true value of the n-dimensional measured variable. The vector ε represents measurement errors such that, for normal functioning of each measurement, the expected value of ε_i is zero and $|\varepsilon_i| \langle\ b_i,$ where b_i is the specified error bound for the measurement m_i.

A measurement of relative consistency between redundant measurements is given by the projection of the measurement vector m onto the left null space of the measurement

matrix H such that the variations in the underlying component Hx in Equation (6.1-1) are eliminated and only the remaining effects of the error vector $\mathcal{E}$ can be observed. An $((\ell - n) \times \ell)$ matrix V is chosen such that its $(\ell - n)$ rows form an orthonormal basis for the left null space of H, for example:

$$VH = 0 \qquad VV^T = I_{\ell - n} \tag{6.1-2}$$

The column space of V is referred to as the "parity space" of H and the projection of m onto the parity space as the "parity vector," which is represented as:

$$p = Vm = V\mathcal{E} \tag{6.1-3}$$

The individual parity vector equations are independent of the true values of x and includes the effects of measurement errors as well as any possible sensor failures [34]. Thus, from Equation (6.1-2), it follows that:

$$V^T V = I_\ell - H[H^T H]^{-1} H^T \tag{6.1-4}$$

The column $v_1, v_2, \ldots, v_\ell$ of V, that are projections of the measurement directions (in R^ℓ) onto the parity space are called failure directions because the failure of the ith measurement m_i implies the growth of the parity vector p in Equation (6.1-3) in the direction of v_i. For nominally unfailed operations, the norm $\|p\|$ of the parity vector remains small. If a failure occurs, p may (in time) grow in magnitude along the failure subspace, which is the subspace spanned by the specific column vectors associated with the failed measurements. If the fault is time-varying, then the failure directions (and hence the failure subspace) may also be time-varying. The increase in the magnitude of the parity

vector signifies abnormality in one or more of the simultaneous redundant measurements, and its direction can be used for identification of abnormal measurement(s). The parity vector in Equation (6.1-3) is related to the familiar residual vector n by:

$$n = V^T p \tag{6.1-5}$$

where $n = m - H\hat{x}$ and $\hat{x} = [H^T H]^{-1} H^T m$, the least-squares estimate of x. From Equation (6.1-2) it follows that the residual vector and parity vector have identical norms, for example:

$$n^T n = p^T p \tag{6.1-6}$$

For the application reported here, only scalar measurements were used. Hence, the dimension of the measured variable x in Equation (6.1-1) is unity. The residual vector can therefore be written as:

$$n = V^T p$$

where:

$$n_i = m_i - \frac{1}{\ell} \sum_{j=1}^{\ell} mj \qquad i = 1,2\ldots,\ell \tag{6.1-7}$$

The residual n_i is thus the difference between the ith measurement and the average of all the redundant measurements.

It can also be shown [35] that the individual parity equations can be described as functions of the signal residuals. This relation is:

$$|P^i|^2 = \sum_{j=1}^{\ell} n_j^2 - \left(\frac{\ell}{\ell - 1}\right) n_i^2 \tag{6.1-8}$$

For normal operation, with no failed sensors, the parity vector tends to be small and the individual P^i are also small. For a set of ℓ measurements it can be shown [36] that ℓ measurements are mutually consistent (fault free) if the following inequality is satisfied:

$$|P|^2 \leq \theta^\ell = \begin{cases} \ell\, b^2 & \text{for even } \ell \\ \left(\dfrac{\ell^2 - 1}{\ell}\right) b^2 & \text{for odd } \ell \end{cases} \tag{6.1-9}$$

Thus, if a failure occurs, the set of ℓ measurements would exhibit inconsistency and the parity vector would grow in magnitude, exceeding the limiting condition θ^ℓ defined by the error bound b.

6.2 Validation Algorithm Development

The parity space approach of section 6.1 can be used to develop an algorithm for fault detection and isolation. The algorithm employs the parity vector, p, as a means of identifying a set of inconsistent or failed measurements. The measurement with the largest residual, within a failed set, can be discarded and the remaining measurements checked for consistency. This process leads to the identification of the largest possible set of consistent measurements. These measurements can be to provide the validated average signal output. The calculational sequence for validation of three assumed independent reactivity measurements with common error bound, b, is given by the following:

1. Calculate the residuals, n_i, and the respective parity vectors, p^i, for the three measured reactivity signals.

2. Compute the consistency threshold using the bound b and ℓ equal to three.

3. Test for measurement consistency. If all the p^i are less than the consistency threshold level, set the validated signal to the average of the three input signals. If one or more of the p^i is greater than the consistency threshold level, the measurement with the largest residual n_i is discarded as a faulty reading.

4. Recalculate the residuals, n_i, and the respective parity vectors, p^i, for the remaining two reactivity measurements.

5. Compute the new consistency threshold again using b but with ℓ equal to two.

6. Test for measurement consistency. If the two p_i's are less than the consistency threshold level, set the validated signal to the average of the remaining two signals. If a p_i is greater than the consistency level then all three signals are inconsistent and the validated reactivity signal is set to a default value equal to the inverse kinetics reactivity signal.

A limitation of this method is that of a "common mode" failure. Common mode failure implies that two of the measurements fail identically. In this instance the validation routine would interpret this condition as a failure of the remaining good signal instead of the failure of two faulty signals.

This algorithm was successfully demonstrated on the MITR-II research reactor in 1983 [37]. The algorithm correctly identified and isolated faulty sensor readings resulting from faulty sensor calibration, gradual drift, increased sensor noise, and total sensor failure. [note: All of these failures were induced as part of an approved experimental procedure.]

6.3 Chapter Summary

The parity method for fault detection and isolation can be easily implemented using the derived relationship of the parity vector to the individual signal residuals. An error bound, b, specified for the measurements is used to define a maximum bound for parity comparison. Faulty signals are indicated when the parity vector for a set of measurements exceeds the calculated consistency threshold. The signal with the largest individual measurement residual is then discarded. The validated signal set can then be averaged to obtain a validated signal which can enhance controller performance.

7. Control Software Implementation

The concept developed in the preceding chapters was written as FORTRAN code so as to provide the block functions shown in the Reactor Neutronic Power Controller Block Diagram, Figure 1.2.1-1. It was desired that the code be capable of running input transient data files available from previous tests conducted on the ACRR. It was also intended that the code be incorporated as a subroutine of the MIT-SNL Period-Generated, Minimum-Time Control Law Code [38]. The software was written in FORTRAN 77.

7.1 Subroutine Description

The developed FORTRAN code consisted of a program main body, six subroutines, and three functions. For model simulation, the main body is capable of reading input data files simulate reactor operation. The calculation steps included in the main body can easily be that incorporated into the MIT-SNL Control Law Code, subroutine "CONPER" [39], to achieve the power controller configuration of Figure 1.2.1-1. The FORTRAN Code, as well as a sample input file, are provided in Appendix D. The purpose of each of the FORTRAN Code Blocks is summarized here.

7.1.1 Program Main Body

This is the controlling routine for the program. It initializes the system model parameters to start a specific power transient. The logical parameter "ALIGN" determines whether or not a predetermined set of thermal parameter coefficients is used in the thermal hydraulic model for predicting reactor fuel temperatures throughout the transient. If set to "TRUE", thermal coefficients are reestimated at each time step by the Kalman estimation

routine. Otherwise the coefficients are not updated. After parameter initialization, the following sequence is followed:

1. Validate the three assumed independent reactivity signals to determine the best estimate of net reactivity as given by variable DKest. Instrumented Synthesis Method reactivity values were not available. Therefore, an average of the current step's and previous step's Inverse Kinetics reactivity was used as a third input signal.

2. Print the desired step output parameters. These could consist of the current time, the individual reactivity signals, the fuel temperature, and the individual estimated thermal parameter coefficients.

3. If variable "ALIGN" is "TRUE", a best estimate of the thermal model parameter coefficients is made and the model is updated to use these values. If variable "ALIGN" is "FALSE", the model parameter coefficients remain unchanged throughout the transient.

4. The Thermal Model of the reactor is advanced to the next time-step. This provides future values of the thermal feedback reactivity and fuel temperature for controller use.

5. At a specified time, the routine reads the next set of data. This data consists of the current-time, the reactor power, the Inverse Kinetics reactivity, and the position of the reactor's transient rod bank.

6. The net reactivity is calculated for this new data via a balance equation.

7. The routine continues by repeating step's one through six until all data in the input file has been processed.

7.1.2 Subroutine Advmodel

The next time step values of the fuel temperature and moderator temperature are calculated using the thermal model equations. The system matrix values of F, H, and E are also advanced using the Kalman Estimation prediction equations.

7.1.3 Subroutine Estmodel

A best estimate of the fuel temperature and the thermal reactor model's parameter coefficients is made via Kalman estimation. This routine is called if the parameter "ALIGN" is "TRUE".

7.1.4 Matrix Math Routines

The Kalman estimation routine uses matrix equations to determine parameter estimates. FORTRAN 77 has no intrinsic matrix functions to accomplish basic matrix mathematics. It was necessary to write basic routines to carry out the operations of matrix addition, transposition, scalar multiplication, and vector multiplication. These matrix mathematics routines were provided by Addmat, Transmat, Multscale, and MatMult respectively. It should be noted that FORTRAN 90 does possess these mathematical operations as intrinsic functions. Should the control scheme be updated to use FORTRAN 90, these four subroutines would be unnecessary.

7.1.5 Functions Reactr (p) and Reactfb (T,Tin)

Function reactr (p) returns the reactivity associated with a given position of the reactor's transient rod bank. This function is called by the main body of the program to determine control rod reactivity for the reactivity balance. Function Reactfb (T,Tin) determines the feedback reactivity associated with increases in the reactor fuel temperature. The reactivity coefficient is as described by Equation 5.1.2-1.

7.1.6 Function Validate

Function Validate returns the values of reactivity resulting from the implementation of the validation algorithm on the three input reactivity signals. Value b specifies the common error bound for reactivity signal validation.

7.2 Chapter Summary

The FORTRAN implementation of the Adaptive Reactor Reactivity Model was developed in FORTRAN 77 and is capable of running input files consisting of current transient-time, reactor power, Inverse Kinetics Reactivity, and transient rod bank position. It determines the resulting reactor fuel temperature and net reactivity via a reactivity balance. The program is capable of estimating model thermal parameter coefficients which are assumed to be constant during transients. The program can also be executed to run using predetermined model parameters.

8. FORTRAN Software Evaluation

The FORTRAN Code developed in Chapter Seven and provided in Appendix D was tested using input data obtained from previous MIT-SNL neutronic power controller tests. These simulations were used to assess the performance of the FORTRAN routines described in Chapter Seven and to show their capacity to support enhanced operation of the MIT-SNL Neutronic Power Control Method. The results of these simulations are summarized here.

8.1 Input File Selection

The input data for FORTRAN Code evaluation was selected from the output data obtained during a series of experimental evaluations that were conducted on the MIT-SNL Period-Generated, Minimum-Time Control Law Code in July 1991. The transient selected was a power increase from three kW to four MW on a 0.695 second period. Reactor power was then held constant for twenty-five seconds. The data available for the transient was provided at 0.045 second intervals over the duration of the transient. The data included reactor power (kW), the calculated inverse kinetics reactivity (millibeta), and the position of the transient rod bank (units). A copy of this data file is provided in Appendix D.

8.2 Parameter Estimation Simulation

As a first test of the FORTRAN Code, the transient was run with initial model thermal parameter coefficients of a_0, b_0, and b_1 set to zero; the logical parameter, "ALIGN", was set to "TRUE"; and the bound for validation was set to two percent.

Parameter initialization was conducted using derived values obtained as detailed in Section 5.1. During this run, the time required for the calculation was also checked to verify that the individual step calculations could be carried out in real-time for controller operation. The thirty second data run required approximately 4.5 seconds to execute. This indicates a single step series calculation time of, on average, 6.75 milliseconds. This meets the sample time criteria for controller operation [40]. The output data was collected at each time step and included reactivity via balance calculation, the validated reactivity, the reactor fuel temperature, and the values of the estimated thermal parameter coefficients (a_o, b_o, b_1). This output file is provided in Appendix D. A comparative plot of the various reactivity signals is shown in Figure 8.2-1. This plot shows oscillations taking place as the estimation routine attempted to determine the best values of reactivity and the thermal parameter coefficient (a_o, b_o, b_1). The oscillation magnitude decreased as the transient progressed. The thermal parameter coefficient values are shown in Figure 8.2-2. Again, the fluctuations in the parameter value are initially large but, decrease as the transient progresses. It is noted that in the two percent input noise simulations of the Kalman estimation routine performed in MATLAB and presented in Section 5.3.1, estimation variations required approximately forty to sixty seconds to decay away. If an additional ten to thirty seconds of data had been available a more precise solution might have been obtainable.

A close examination of the reactivity outputs revealed the proper operation of the validation routine. When all three values were within the required bounds, as calculated using b, a three signal estimate was provided for the variable DKest. During oscillations

of the balance reactivity, caused by parameter estimation, the routine isolated the balance reactivity signal and provided a two signal estimate for the variable DKest.

As a final evaluation of the routine's ability to converge to a correct solution, the FORTRAN Code was run a second time with the thermal parameter coefficients initialized to the final values obtained during the first estimation run. The logical parameter "ALIGN" was set to "FALSE" so the simulated transient could be modeled using the previously determined thermal parameters. The output reactivity values from this simulation are shown in Figure 8.2-3. The modeled balanced reactivity differs from the actual inverse kinetics reactivity by approximately ten percent. It is possible that if a more precise set of thermal parameter coefficients could have been obtained the model's performance would have provided a more accurate approximation to the reactivity response. A longer simulation providing more accurate coefficient values could lead to a better fit of modeled reactor conditions to the actual inverse kinetics values. It should also be noted, however, that the estimation routine relies on the accuracy of the fuel temperature reactivity coefficient relationship given in equation 5.1.2-1. Errors in this relation could also cause the observed differences between the calculated balance reactivity and the actual inverse kinetics reactivity. It should also be noted that no attempt is made to verify the accuracy of the control rod reactivity obtained by the Function Reactr (p). A temperature dependence of transient bank rod worth could also lead to a modeling error. These possibilities would require additional investigation.

Figure 8.2-1 ACRR Net Reactivity Transient Response

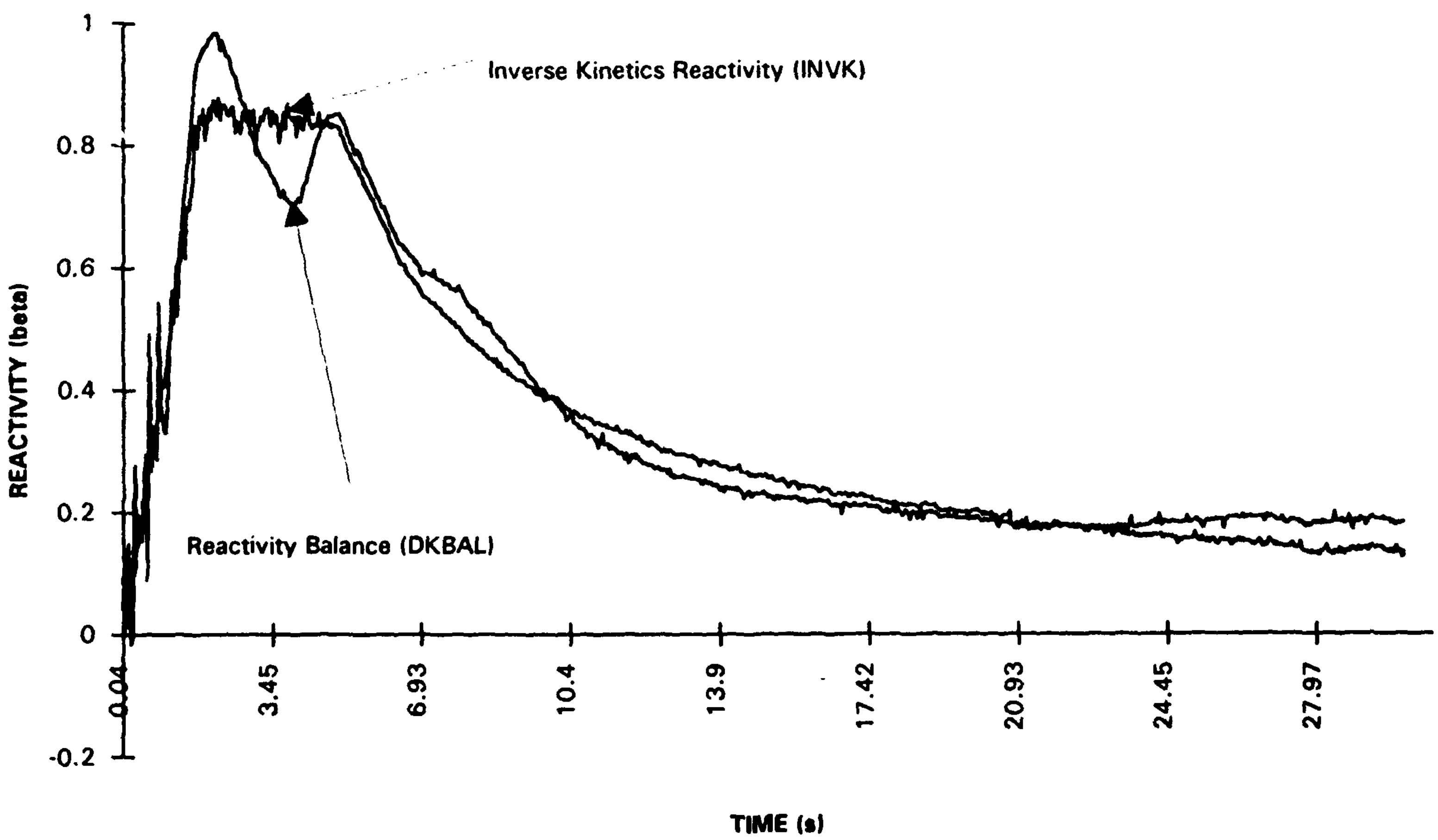


Figure 8.2-2 Parameter Estimation Response

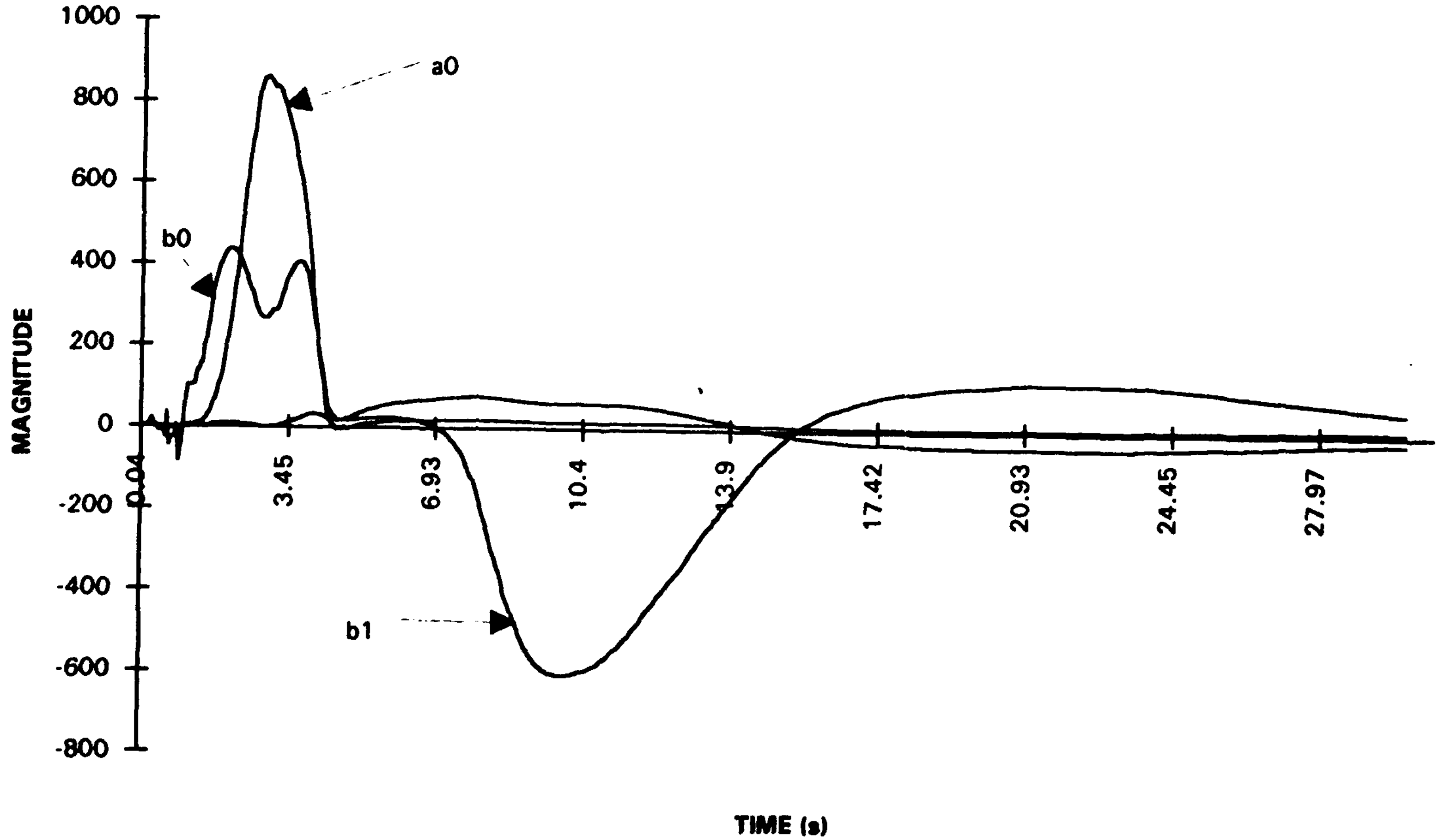
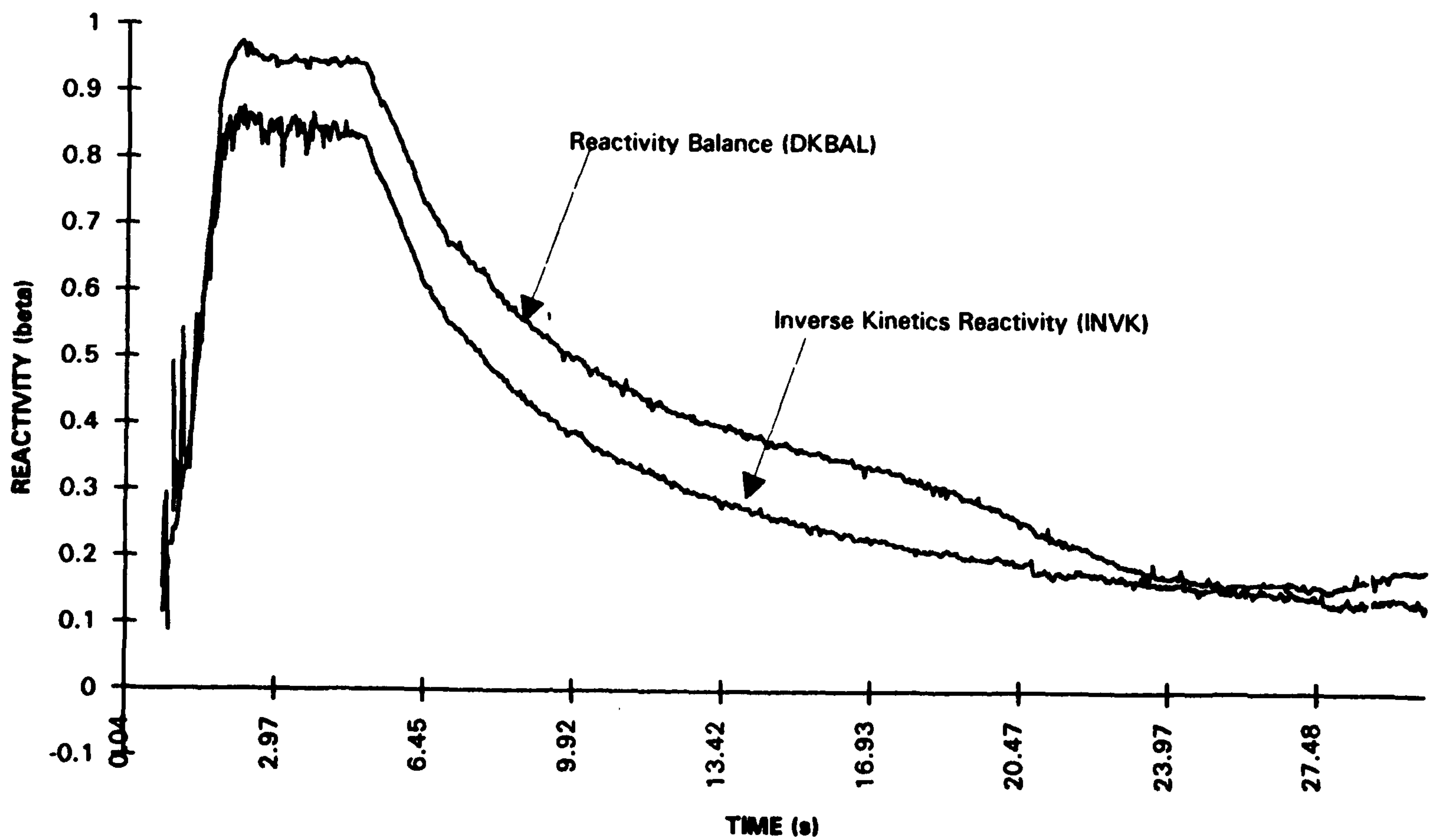


Figure 8.2-3 Net Reactivity - Balance Model with Constant Parameters



8.3 Chapter Summary

The FORTRAN Code implementation of the thermal-hydraulic reactor reactivity balance model was run using input data from previously conducted MIT-SNL period-generated, minimum-time control law code testing on the ACRR. These simulations showed the ability of the reactivity balance model using the Kalman estimation of model thermal parameter coefficients, to converge to an actual dynamic reactivity solution. Convergence after thirty seconds of estimation was to within approximately 10% of the assumed actual system reactivity. Additional investigation is indicated to determine if longer simulation runs would provide more accurate model solutions. Investigation of other sources of modeling error which are currently not estimated may also be warranted.

9. Sensor Optimization for Automatic Fault Detection

Chapter Six described the parity space method of fault detection and isolation that is used to provide signal validation for the assumed independent reactivity signals. It would be desirable to implement the closed form of the MIT-SNL period-generated, minimum-time control law code to provide on-line fault detection and isolation. To achieve this requires an examination of both the inputs available to the control system as well as the method to be used to achieve fault diagnostics.

9.1 Method of Fault Detection

Methods other than the parity space approach can be used to provide on-line fault detection for improved system performance. Some of these methods include failure sensitive filters, statistical innovations, and sequential hypothesis testing [41]. Often the method selected is based on the desired response of the detection system that is to be employed. In general, there are usually two conflicting considerations. These are the speed at which a system responds to a fault and the degree of degradation needed to allow a fault to be detected. Systems which require a high degree of reliability such as aircraft or nuclear control systems demand input redundancy to ensure rapid fault detection with a minimum impact of false alarms. It was this consideration which lead to the use of the parity space approach outlined in Chapter Six. To implement the parity space approach, a minimum configuration of redundant sensors must be available.

9.2 Minimum Sensor Employment for Fault Detection

The MIT-SNL Period-Generated, Minimum-Time Control Law Code relies on inputs from reactor power, net reactivity, the rate of thermal feedback reactivity, and rod position and speed to provide the proper rod control signal. The power signals from the nuclear instrumentation are instrumental in providing input for reactivity calculations as well as in determining the deviation of the reactor from the desired power level. It is necessary that a continuous uninterrupted power signal be available across the range of operation. Most nuclear instruments cover a range of approximately four decades of power. To achieve adequate sensitivity and accuracy to power level changes across a wide range of power levels (as many as ten decades of power) a combination of instruments is used. These nuclear instruments are usually divided into source, intermediate, and power ranges. A relationship can easily be derived to generate a single, continuos neutronic power level signal from these three detector ranges [42]. Furthermore, the ranges are designed so that overlap exists from one range to another. Thus, for operation in the intermediate range, power signal validation could be conducted using source or power range instruments that exhibit overlap. It should be noted that for operation high in the power range or low in the source range, signal validation would require an additional sensor. This sensor could either be a direct neutronic power signal or an indirect signal derived from an analytic model. As an example, reactor power could be predicted using the known reactivity and the space independent kinetics equations [43]. Use of an analytic model in place of a direct signal input eliminates the need to provide additional sensors for the sole purpose of signal validation. Thus, for nuclear instrumentation, a minimum implementation for fault detection over the entire range of

operation could consist of two independent channels of source, intermediate, and power range with an analytic model capable of predicting the neutronic power level using a validated reactivity input. These validated power signals along with the validated reactivity inputs would offer a minimum sensor implementation for on-line detection for the MIT-SNL period-generated, minimum-time control law.

9.3 Chapter Summary

The parity space approach of signal validation for systems with redundant measurements provides a rapid means of sensor fault detection and isolation. The MIT-SNL neutronic power controller requires both validation of net reactivity and reactor power input signals to provide enhanced system performance. This implementation would require a minimum of two sets of power, intermediate and source range nuclear instrument channels along with an analytic model for reactor power prediction.

10. Summary, Conclusions, and Recommendations for Future Research

10.1 Summary

This report summarized the development and demonstration of an improved reactor analytic model for the prediction of thermal feedback reactivity. The output of this model was used in a reactivity balance to produce a net reactivity signal. This signal was employed along with two additional, assumed independent, net reactivity estimation methods in a parity-space fault detection algorithm to give a validated net reactivity. The end use of this validated net reactivity signal is to provide enhanced operation of the MIT-SNL period-generated, minimum-time, neutronic power controller. The analytic heat deposition model for prediction of thermal feedback reactivity included a Kalman state estimation routine to provide real-time model adaptation to compensate for modeling errors or parameter drift. The concepts used in the adaptive analytic reactivity balance model were verified using the PC-based math software MATLAB and MATHCAD, as well as, a finite difference, heat transfer code, HEATING 5. An adaptive analytic reactivity model of the ACRR was implemented in FORTRAN 77. A simulation of this model implementation was conducted. Simulation input was provided from previous tests of the MIT-SNL period-generated, minimum-time, neutronic power controller on the ACRR conducted in July 1991.

10.2 Conclusions

The lumped average core parameter, heat deposition model of the ACRR, modeled using MATHCAD, was compared to a nodal, finite difference, heat transfer model of the ACRR, modeled using HEATING 5. The lumped parameter, average core value model predicted average core fuel temperatures to within approximately two percent of the values obtained using the nodal finite difference method. This verification was shown for both slow and rapid power transients.

The Kalman estimation routine employed to provide thermal model adaptation was simulated using MATLAB. The simulation verified the ability of the Kalman state estimation routine to determine analytic model thermal parameters for the purpose of on-line, real-time model error correction. The simulations used input power and system thermal feedback reactivity signals, sampled every 50 milliseconds, and corrupted with two percent white noise. The estimation routine determined the system thermal parameter coefficients in approximately sixty-five seconds. These estimated parameter coefficients when used in the analytic reactivity model, produced thermal feedback reactivities that were within the two percent noise band of the input feedback reactivity.

The final system simulation of the adaptive analytic reactivity balance model and the reactivity validation routine confirmed the ability of the validation routine to reject faulty reactivity input signals. The adaptive analytic reactivity balance model determined best estimates of the model's thermal parameter coefficients during a 30 second simulation. This simulation used input data obtained from previous MIT-SNL period-generated, minimum-time, neutronic power controller tests. The length of time required by the

routine to carry out the calculations necessary for a single time step was on average 6.75 milliseconds. This met the sample time criteria for controller operation. The estimated thermal parameter coefficients were in turn used to produce a reactivity balance model that was capable of predicting system reactivity to within approximately ten percent of the actual system values. More accurate model thermal parameter coefficients could be obtained if the estimation were performed for approximately sixth-five seconds of input data.

10.3 Recommendations for Future Research

The following recommendations involve areas associated with this report that warrant further research:

1. Additional simulations of the adaptive estimation routine to determine an optimum set of Kalman estimation parameters that produce the most efficient and robust response. Parameters affecting estimation routine response include, the noise covariance matrix (R) and the initial value of the error covariance matrix (E). Limiting the allowed magnitude of the estimated thermal parameter coefficients could also be considered to enhance routine response.

2. Additional simulations of the adaptive estimation routine using real ACRR data over longer transient intervals. Simulations should address determination of a minimum time required for the estimation routine to determine the model's thermal parameter coefficients that are capable of predicting future reactivity transients to within two percent of the inverse kinetics reactivity values.

3. Incorporation of the Adaptive Reactivity Model FORTRAN Code implementation into the MIT-SNL Period-Generated, Minimum-Time, control code. The combined code could be demonstrated on the ACRR to determine the benefits of this reactivity estimation and validation scheme on controller performance.

References

1. Bernard, J. A., Formulation and Experimental Evaluation of Closed-Form Control Laws for the Rapid Maneuvering of Reactor Neutronic Power, MIT Nuclear Reactor Laboratory Report Number MITNRL-030, Cambridge, MA, 1989, p 133.

2. Bernard, J.A., Startup and Control of Nuclear Reactors Characterized by Space Independent Kinetics, MIT Nuclear Reactor Laboratory Report Number MITNRL-039, Cambridge, MA, 1990, p 186.

3. Ray, A. and R. Luck (1991) "An Introduction to Sensor Signal Validation in Redundant Measurement Systems", IEEE Control Systems Magazine, 11(2) : pp 43-49.

4. Bernard, J.A. and D.D. Lanning, "Considerations in Design and Implementation of Control Laws for the Digital Operation of Research Reactors", Nuclear Science and Engineering, Vol. 110, Nov. 4, Apr. 1992, pp 425-444.

5. Bernard, J.A., "Non-Linear Control of Neutronic Power in Reactors Described by Space-Independent Kinetics", International Journal Control-Theory and Advanced Technology (C-TAT), Vol. 8, No. 3, Sept. 1992, pp 495-511.

6. Lau, S.H., J.A. Bernard and D.D. Lanning (1991). "Experimental evaluation of feedforward control for the trajectory tracking of power in nuclear reactors". Proc. 26th Inter-society Energy Conversion Engineering Conference (IECEC), August, Boston, MA, 5, 13-19).

7. Henry, A. F., Nuclear Reactor Analysis, MIT Press, Cambridge, MA. 1975, p 78.

8. Ibid. p 304.

9. Ibid. p 299.

10. Ibid. p 305.

11. Ibid. p 302.

12. Sastre, C. A., "The Measurement of Reactivity", Nuclear Science and Engimeering, Vol. 8, pp. 443-447, Nov 1960.

13. Ibid. p 113.

14. Henry, A. F., Lanning, D.D., and Bernard, J.A., "Experimental Evaluation of an Instrumental Synthesis Method for the Real-Time Estimation of Reactivity", Proposal Submitted to the U.S. Department of Energy.

15. Jacqmin, R. P., "Combined Use of In-Core Neutron Detectors and Precomputed, Three-Dimensional, Nodal Flux-Shapes for the On-line Determination of the Neutron Distribution in Light-Water Reactors", MIT, Cambridge, MA, 1991, pp 2-5.

16. Avallone, E.A. and Baumeister, T., "Mark's Standard Handbook for Mechanical Engineers", McGraw-Hill Book Company, New York, NY, 1987, p 4-5.

17. Todress, N. E. and Kazimi, M. S., "Nuclear Systems - I", Hemispere Publishing Company, New York, NY, 1990, p 84.

18. Anderson, B. D. and Moore, J. B., Optimal Filtering, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1979, p 29.

19. Verghese, G., Dynamic Systems, MIT course number 6.241, Classnotes, (Fall 1992).

20. Anderson, B. D. and Moore, J. B., Optimal Filtering, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1979, p 39.

21. Ibid. p 195.

22. Sandia National Laboratories (SNL) Annular Core Research Reactor (ACRR) Safety Analysis Report, Chapter Four, (Draft Copy - currently under review)

23. American Society for Metals, "Metals Handbook: Vol 2: Properties and Selection: Non-Ferrous Alloys and Pure Metals", American Society for metals, Metals Park, Ohio, pp 777-778.

24. Guyer, E. C., "Handbook of Applied Thermal Design", McGran-Hill Book Company, New York, NY, 1989, p 5-31.

25. Vargaftif, N. B., "Thermophysical Properties of Liquids and Gases", Hemispere Publishing Corporation, Washington, D.C., 1975.

26. Todress, N. E. and Kazimi, M. S., "Nuclear Systems - I", Hemispere Publishing Company, New York, NY, 1990, p 84.

27. Sandia National Laboratories (SNL) Annular Core Research Reactor (ACRR) Safety Analysis Report, Chapter Four, (Draft Copy - currently under review) p 4-57.

28. Ibid. p 4-53.

29. McCrory, F., Sandia National Laboratories, Reactor Applications Department, personnel communication by phone, (July1992).

30. Sandia National Laboratories (SNL) Annular Core Research Reactor (ACRR) Safety Analysis Report, Chapter Four, (Draft Copy - currently under review) p 4-71.

31. Turner, W. D. and M. Siman-Tov, "Heating 5 -- An IBM 360 Heat Conduction Program", Oak Ridge National Laboratory, Oak Ridge,Tennesse,February 1971.

32. Sandia National Laboratories (SNL) Annular Core Research Reactor (ACRR) Safety Analysis Report, Chapter Four, (Draft Copy - currently under review) p 4-44.

33. Polenta, H. P., Ray, A. and J. A. Bernard, "Fault Detection System For Argentine Reasearch Reactor Instrumentation", American Institute of Physics, CONF 930103, 1993.

34. Ray, A., Desai, M.N., and J. Dejst, "Fault Detection and Isolation in a Nuclear Reactor", Journal of Energy, Vol. 7, No. 1, Jan. - Feb. 1983, p 81.

35. Ibid. p 82.

36. Ibid. p 82.

37. Ibid. p 79.

38. Bernard, J. A., Formulation and Experimental Evaluation of Closed-Form Control Laws for the Rapid Maneuvering of Reactor Neutronic Power, MIT Nuclear Reactor Laboratory Report Number MITNRL-030, Cambridge, MA, 1989.

39. Ibid. p 145.

40. Ibid. p 136.

41. Willsky, A. S., "A Survey of Design Methods for Failure Detection in Dynamic Systems", Automatica, Vol. 12, Nov. 1976, pp 601-611.

42. Bernard, J. A., Formulation and Experimental Evaluation of Closed-Form Control Laws for the Rapid Maneuvering of Reactor Neutronic Power, MIT Nuclear Reactor Laboratory Report Number MITNRL-030, Cambridge, MA, 1989 p 149.

43. Ibid. p 42.

44. Jacqmin, R. P., "Combined Use of In-Core Neutron Detectors and Precomputed, Three-Dimensional, Nodal Flux-Shapes for the On-line Determination of the Neutron Distribution in Light-Water Reactors", MIT, Cambridge, MA, 1991, pp 2-5.

45. Kaplian S., O. J. Marlowe, and J. A. Bewick, "Application of Synthesis Techniques to Problems Involving Time-Dependence", Nuclear Science and Engineering, 18, 163 (1964).

46. Yasinski J. B. and A. F. Henry, "Some Numerical Experiments Concerning Space-Time Reactor Kinetics Behavior", Nuclear Science and Engineering, 22, 171 (1965).

47. Henry A. F., Nuclear-Reactor Analysis, MIT Press, Cambridge, MA (1975).

48. Stacey W. M., Jr., Space-Time Nuclear Reactor Kinetics, Academic Press, New York, NY (1969).

49. Ryals H. W., "Approximation of Nuclear Flux Distributions in Operating Power Reactors", Transactions of the American Nuclear Society, 14, 750 (1971).

50. Levine M. M. and D. J. Diamond, "Reactor Power Distribution From Analysis of In-Core Detector Readings", Nuclear Science and Engineering, 47, 415 (1972).

51. Kugler G., "Commissioning and Early Operating of the Bruce A Flux-Mapping System", Proceedings of IAEA International Symposium on Nuclear Power Plant Control and Instrumentation, IAEA-SM-226/101, Volume I, 463, Cannes, France (1978).

52. Knob P. J., R. D. Neef, and H. Schaal, "Development and test of the Three-Dimensional Computer Code ZELT-3D for Unfolding Power Distributions Using Side Reflector Instrumentation Signals", Nuclear Technology, 64, 3, 217 (1984).

53. Bonalumi R. A. and N. P. Kherani, "Rational Mapping (RAM) if In-Core Data", Nuclear Science and Engineering, 90, 47 (1985).

54. Hotte G. A. Baudouin, G. Parent, and C. Ngo-Trong, "Gentilly Core Management Based on Diffusion Theory and On-Line Monitoring (SIMEX)", Proceedings of the Topical Meeting on Advances in Fuel Management, Pinehurst, NC (1986).

Appendix A

$i := 0..3$ $\qquad j := 0..2$ $\qquad k := 0..3$ $\qquad t := 0..720$

$run_i :=$	$N_i :=$	$Tmod_i :=$	$Tfuel_k :=$	$H_k :=$
0.0	100000	23.4	78.9	128.59927
10.0	2000000	23.8	244.5	165.7129
480.0	2000000	40.9	392.8	198.72629
720.0	2000000	40.9	607.8	251.39943
			955.0	315.98251

$Tf_j :=$	$Cp_j :=$
10	836
50	920.48
100	962.32
200	1046.0
300	143.63
400	1202.9
500	1263.56
600	1310.99
700	1350.83
800	1385.95
900	1417.91
1000	1447.66

$\rho := 3550.0$ $\qquad V := 0.09866089$ $\qquad A := 14.01098$

$\tau := 0.00000063$ $\qquad \theta f_0 := 78.9$

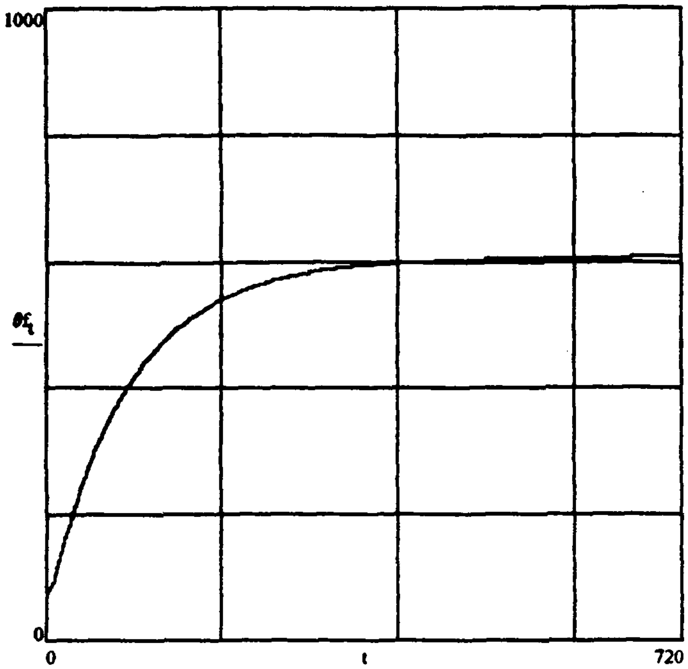
$\theta mod(t) := linterp(run, Tmod, t)$

$h(t, \theta f) := linterp(Tfuel, H, \theta f_t)$

$pwr(t) := linterp(run, N, t)$

$Cpf(t, \theta f) := linterp(Tf, Cp, \theta f_t)$

$$\theta f_{t+1} := \frac{\theta mod(t)\cdot h(t,\theta f)\cdot A + (1-\tau)\cdot pwr(t) - \theta f_t\cdot A\cdot h(t,\theta f)}{\rho\cdot V\cdot Cpf(t,\theta f)} + \theta f_t$$



$\theta f_0 = 78.9$

$\theta f_{10} = 104.095$

$\theta f_{30} = 202.732$

$\theta f_{60} = 315.416$

$\theta f_{120} = 455.019$

$\theta f_{180} = 526.861$

$\theta f_{240} = 563.995$

$\theta f_{300} = 583.503$

$\theta f_{360} = 594.077$

$\theta f_{420} = 600.126$

$\theta f_{480} = 603.883$

$\theta f_{540} = 606.1$

$\theta f_{600} = 607.225$

$\theta f_{660} = 607.795$

$\theta f_{720} = 608.084$

$i := 0..3$ $j := 0..2$ $k := 0..3$ $t := 0..720$

run_i
0.0
13.0
26.0
720.0

N_i
1
6400000000
1
1

$Tmod_i$
20.0
20.0
20.0
20.0

$Tfuel_k$
78.9
244.5
392.8
607.8
955.0

H_k
128.59927
165.7129
198.72629
251.39943
315.98251

Tf_j
10
50
100
200
300
400
500
600
700
800
900
1000

Cp_j
836
920.48
962.32
1046.0
1143.63
1202.9
1263.56
1310.99
1350.83
1385.95
1417.91
1447.66

$\rho := 3550.0$ $V := 0.09866089$ $A := 14.01098$

$\tau := 0.00000063$ $\theta f_0 := 20.0$

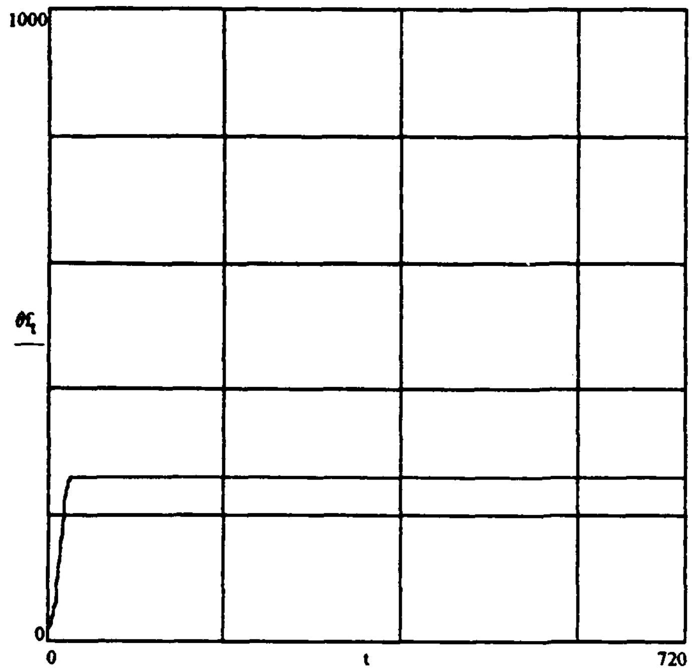
$\theta mod(t) := \mathrm{linterp}(run, Tmod, t)$

$h(t, \theta f) := \mathrm{linterp}(Tfuel, H, \theta f_t)$

$pwr(t) := \mathrm{linterp}(run, N, t)$

$Cpf(t, \theta f) := \mathrm{linterp}(Tf, Cp, \theta f_t)$

$$\theta f_{t+1} := \frac{\theta mod(t)\cdot h(t,\theta f)\cdot A + (1-\tau)\cdot pwr(t) - \theta f_t\cdot A\cdot h(t,\theta f)}{\rho\cdot V\cdot Cpf(t,\theta f)}\cdot 0.001 + \theta f_t$$



$\theta f_0 = 20$

$\theta f_{13} = 137.463$

$\theta f_{26} = 260.447$

$\theta f_{30} = 260.441$

$\theta f_{100} = 260.337$

$\theta f_{500} = 259.744$

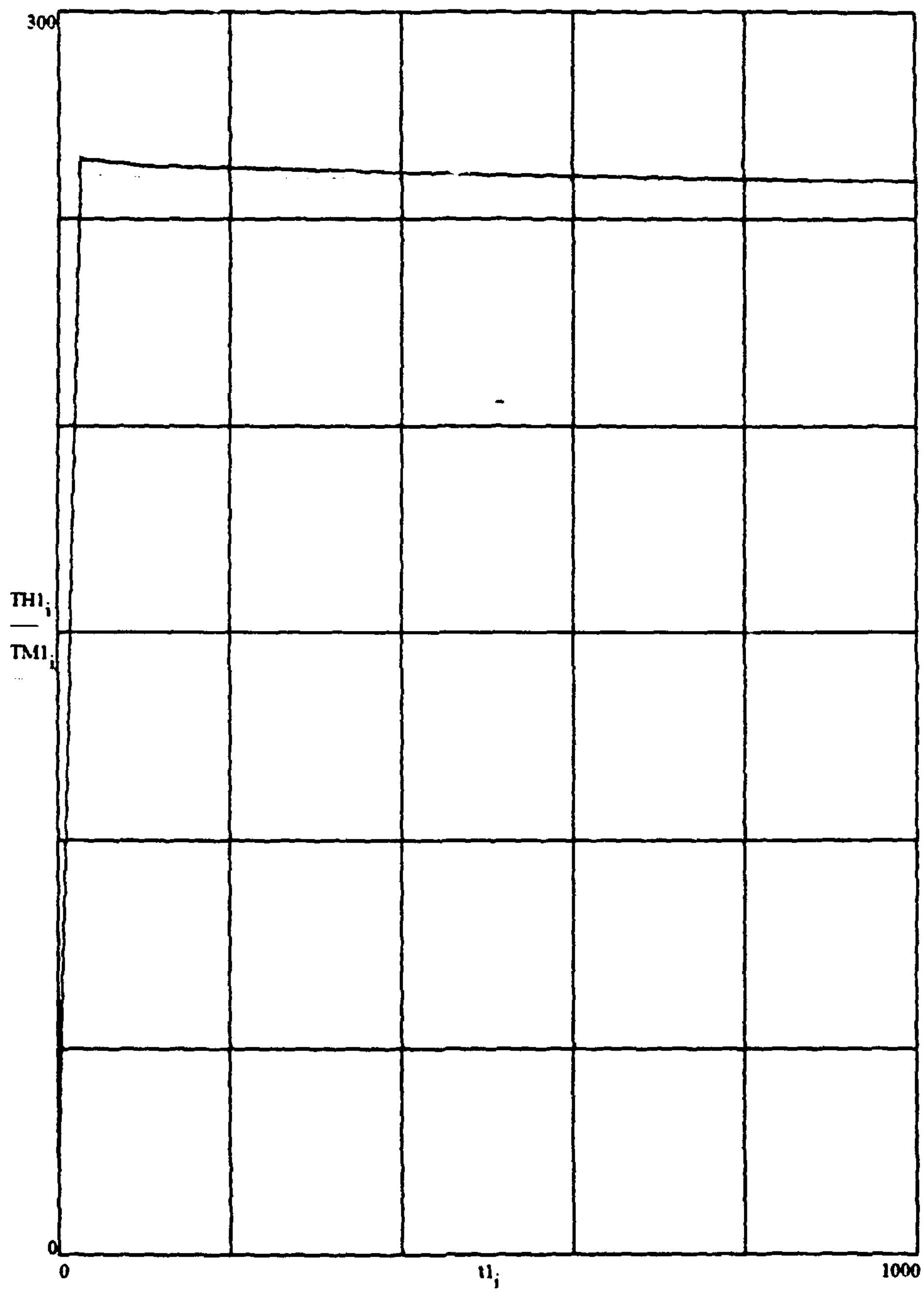
$\theta f_{720} = 259.419$

$i := 0..6$ $j := 0..14$

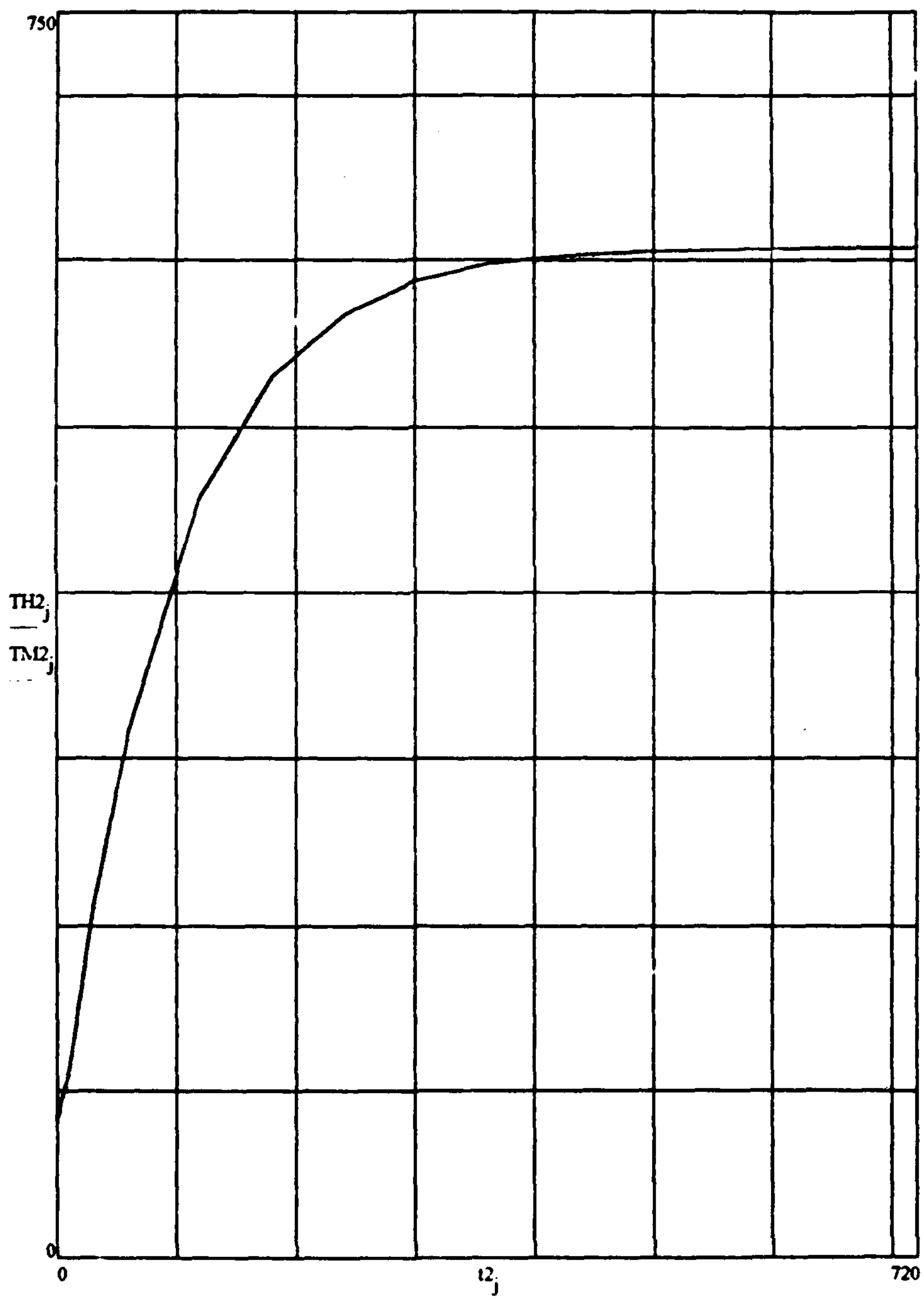
$t1_i$ =	$TH1_i$ =	$TM1_i$ =
0	20.0	20.0
13	139.94	137.46
26	264.64	260.45
30	264.55	260.44
100	263.19	260.34
500	260.52	259.74
1000	259.06	259.01

$t2_j$ =	$TH2_j$ =	$TM2_j$ =
0	84.85	78.9
10	112.77	104.10
30	209.65	202.73
60	319.28	315.42
120	456.45	455.02
180	529.23	526.86
240	567.42	563.99
300	587.12	583.50
360	597.19	594.08
420	602.34	600.13
480	604.98	603.88
540	606.34	606.1
600	607.02	607.23
660	607.38	607.8
720	607.56	608.08

HEATING5 and Heat Balance Equation temperatures
6400 MW pulse - 13 msec width @ half peak power



HEATING5 and Heat Balance Equation temperatures
100 KW to 2 MW steady state -10 sec power ramp

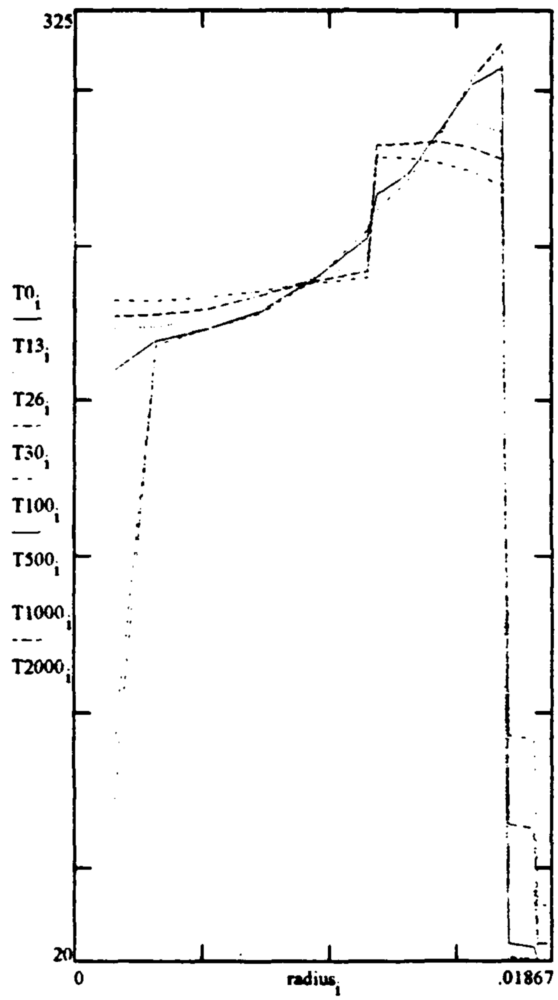


i := 0.. 14

$radius_i$ =	$T0_i$ =	$T13_i$ =	$T26_i$ =	$T30_i$ =	$T100_i$ =	$T500_i$ =
.00159	20	27.62	71.4	87.86	209.32	222.91
.00318	20	115.82	217.84	217.9	218.92	223.12
.005242	20	118.35	222.75	222.76	223.01	225.7
.007305	20	120.7	227.47	227.52	228.33	231.55
.009367	20	126.09	238.13	238.18	238.86	239.18
.01143	20	134.79	254.67	254.49	251.75	244.06
.01181	20	137.31	260.71	261.05	265.83	278.61
.013048	20	142.99	271.16	271.25	273.07	281.25
.014285	20	150.45	285.59	285.66	286.6	286.11
.015523	20	159.87	303.36	303.28	301.28	289.16
.01676	20	166.53	315.02	314.44	306.36	286.51
.016967	20	20.15	21.06	21.39	25.6	45
.017963	20	20.02	20.26	20.42	24.31	43.79
.01816	20	20	20	20	20.06	21.7
.01867	20	20	20	20	20.03	21.5

$T1000_i$ =	$T2000_i$ =
226.8	231.74
226.96	231.82
228.94	232.81
233.37	234.96
238.15	237.26
240.93	238.93
281.96	277.87
282.68	277.82
282.85	276.33
281.36	273.46
277.26	269.29
64.04	92.32
62.87	91.2
25.95	38.06
25.59	37.49

ACRR FUEL PIN TEMP. PROFILE - 6400 MW PULSE - 0 TO 2 SEC



FUEL PIN RADIUS
(METERS)

Appendix B

```
ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half
  100    2    8    4         1    1    1
    9    2         1    8
         8              1000
    3  1000   1e-5   1.9  0.001   1.1   0.0   2.0
    1    1   0.0 0.00318    0.03.1415926
    1
    2    2 0.00318 0.01143    0.03.1415926
    1    1
    3    1 0.01143 0.01181    0.03.1415926
    1
    4    2 0.01181 0.01676    0.03.1415926
    1    1
    5    1 0.016760.0169669    0.03.1415926
    1
    6    30.01696690.0179631    0.03.1415926
    1
    7    10.0179631 0.01808    0.03.1415926
    1
    8    4 0.01808 0.01861    0.03.1415926
    1              1
    1  HEVOID            5.192e3    -6    -7
    2   FUEL   24.0  3550.0                    -1
    3  NBCUP         8570.0    270    -5
    4    SS      7950.0    502    -2
    1   1.0    -3          -4
    1   20.0
    1    1   1.0    -8
  1.0                        2
    1
  0.0 0.00318 0.01143 0.01181 0.016760.01696690.0179631 0.01808
0.01861
    2    4    1    4    1    1    1    1
  0.03.1415926
    1
    1    2
    2   1.0     30.2797728
    1   25
  10.0  836.80   50.0 920.480   100.0 962.320   200.0  1046.0
 300.01143.6266   400.0  1202.9   500.0 1263.568   600.01310.9866
 700.01350.8342   800.0  1385.95   900.01417.9111   1000.01447.6640
1100.01472.0072  1200.01495.7800  1300.01519.1138  1400.01542.1028
1500.01562.0266  1600.01584.6900  1700.01604.6870  1800.01624.7866
1900.01644.9726  2000.01631.4000  2100.01681.5695  2200.01700.2254
2310.01720.6926
    2    4
  20.0   17.3   100.0   17.3   200.0   17.3   300.0   19.0
    3    3
  0.010.106046   0.0136.4679e10   0.02610.106046
    4   11
0.00318   0.81   0.004   0.82   0.006   0.84   0.008   0.86
  0.01   0.92 0.01143   0.98 0.01181   1.0   0.012   1.0
 0.014    1.1   0.016   1.24   0.017   1.28
    5    6
```

```
  0.0    52.3   100.0    54.4   200.0    56.5   300.0    58.6
 400.0    60.7  1000.0    72.7
   6     18
 20.0   0.072   100.0   0.072   200.0   0.115   300.0   0.151
 400.0   0.184   500.0   0.218   600.0   0.250   700.0   0.278
 800.0   0.304   900.0   0.330  1000.0   0.354  1200.0 0.000405
1400.0 0.000455  1600.0 0.000502  1800.0 0.000543  2000.0   0.579
2500.0   0.657  3000.0   0.745
   7      3
 20.0 0.32828  1200.0 0.16334  2600.0 0.167532
   8      2
  0.0   20.0   10.0   20.0
  0.0   0.013  0.026   0.03    0.1    0.5    1.0    2.0
   1      1
0.00001  0.001 0.00001
  0.1    1.1
□
```

ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.

```
  100     2     8     4           1     1     1
    9     2           1     8
         17                 1000
    3   1000    1e-5    1.9    0.1    1.1    0.0   720.0
    1     1    0.0 0.00318    0.03.1415926
    1
    2     2 0.00318 0.01143     0.03.1415926
    1     1
    3     1 0.01143 0.01181     0.03.1415926
    1
    4     2 0.01181 0.01676     0.03.1415926
    1     1
    5     1 0.016760.0169669     0.03.1415926
    1
    6     30.01696690.0179631     0.03.1415926
    1
    7     10.0179631 0.01816     0.03.1415926
    1
    8     4 0.01816 0.01867     0.03.1415926
    1                 1
    1  HEVOID              5.192e3     -6     -7
    2   FUEL    24.0  3550.0                       -1
    3   NBCUP         8570.0    270    -5
    4    SS       7950.0    502    -2
   11.01060e6     -3           -4
    1    23.4
    1     1    1.0     -8
  1.0                          2
    1
   0.0 0.00318 0.01143 0.01181 0.016760.01696690.0179631 0.01816
 0.01867
    2     4     1     4     1     1     1     1
   0.03.1415926
    1
    1     2
    2    1.0      30.2797728
    1    25
  10.0  836.80    50.0 920.480    100.0 962.320    200.0  1046.0
  300.01143.6266   400.0  1202.9   500.0 1263.568   600.01310.9866
  700.01350.8342   800.0  1385.95   900.01417.9111   1000.01447.6640
 1100.01472.0072  1200.01495.7800  1300.01519.1138  1400.01542.1028
 1500.01562.0266  1600.01584.6900  1700.01604.6870  1800.01624.7866
 1900.01644.9726  2000.01631.4000  2100.01681.5695  2200.01700.2254
 2310.01720.6926
    2     4
  20.0    17.3   100.0    17.3   200.0    17.3   300.0    19.0
    3     3
   0.00.7806946    10.0    20.0    60.0    20.0
    4    11
0.00318    0.81   0.004    0.82   0.006    0.84   0.008    0.86
  0.01    0.92 0.01143    0.98 0.01181    1.0   0.012    1.0
 0.014    1.1   0.016    1.24   0.017    1.28
    5     6
```

```
  0.0    52.3   100.0    54.4   200.0    56.5   300.0    58.6
 400.0    60.7  1000.0    72.7
   6     18
  20.0   0.072   100.0   0.072   200.0   0.115   300.0   0.151
 400.0   0.184   500.0   0.218   600.0   0.250   700.0   0.278
 800.0   0.304   900.0   0.330  1000.0   0.354  1200.0 0.000405
1400.0 0.000455  1600.0 0.000502  1800.0 0.000543  2000.0   0.579
2500.0   0.657  3000.0   0.745
   7      3
  20.0 0.32828  1200.0 0.16334  2600.0 0.167532
   8      3
  0.0    23.4   480.0    40.9   720.0    40.9
  0.0     5.0    10.0    20.0    30.0    60.0   120.0   180.0
 240.0   300.0   360.0   420.0   480.0   540.0   600.0   660.0
 720.0
   1      1
0.00001   0.001 0.00001
  0.1     1.1
```

```
 CURRENT TIME = 19:41:56.83                    DATE : 9/14/1992
HEATING5, A MULTI-DIMENSIONAL HEAT CONDUCTION CODE WITH TEMPERATURE-DEPENDENT THERMAL PROPERTIES,
NON-LINEAR AND SURFACE-TO-SURFACE BOUNDARY CONDITIONS AND CHANGE-OF-PHASE CAPABILITIES.
THIS VERSION OF THE CODE IS DESCRIBED IN ORNL/TM/CSD-15.
THE TRANSIENT SOLUTION CAN BE CALCULATED BY AN IMPLICIT TECHNIQUE (CRANK-NICOLSON OR
BACKWARDS EULER) FOR PROBLEMS WITH MATERIALS WHICH ARE NOT ALLOWED TO UNDERGO A PHASE CHANGE.
THE ONE-DIMENSIONAL R SPHERICAL MODEL WAS ADDED NOV. 75. THIS MODEL MAY BE ACCESSED
BY SPECIFYING NGEOM = 10 IN THE INPUT DATA.
HEATING5 WAS WRITTEN BY

    W.D. TURNER
    D.C. ELROD
    I.I. SIMAN-TOV
    COMPUTER SCIENCES DIVISION
    UNION CARBIDE CORPORATION, NUCLEAR DIVISION
          OAK RIDGE, TENNESSEE 37830

THIS VERSION OF HEATING CAN HANDLE A MAXIMUM OF    400 LATTICE POINTS.

INPUT RETURN

  JOB DESCRIPTION-- ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.
  GEOMETRY TYPE NUMBER      2 (OR RT  )
  NUMBER OF REGIONS      8
  NUMBER OF MATERIALS      4
  NUMBER OF HEAT GENERATION FUNCTIONS      1
  NUMBER OF INITIAL TEMPERATURE FUNCTIONS      1
  NUMBER OF DIFFERENT KINDS OF BOUNDARIES      1
  THIS PROBLEM INVOLVES TEMPERATURE-DEPENDENT PROPERTIES.
  NUMBER OF POINTS IN GROSS X OR R LATTICE      9
  NUMBER OF POINTS IN GROSS Y OR THETA LATTICE      2
  NUMBER OF POINTS IN GROSS Z LATTICE      0
  NUMBER OF ANALYTIC FUNCTIONS      1
  NUMBER OF TABULAR FUNCTIONS      8
  NUMBER OF TRANSIENT PRINTOUTS SPECIFIED      17
  TEMPERATURES OF SELECTED NODES WILL BE MONITORED EVERY  1000 ITERATIONS OR TIME STEPS.
  PROBLEM TYPE NUMBER      3
  STEADY STATE CONVERGENCE CRITERION  1.00000000D-05
  MAXIMUM NUMBER OF STEADY-STATE ITERATIONS   1000
  NUMBER OF ITERATIONS BETWEEN TEMPERATURE DEPENDENT
  PARAMETER EVALUATIONS FOR STEADY STATE CALCULATIONS      0
  INITIAL OVERRELAXATION FACTOR (BETA) FOR STEADY STATE CALCULATIONS  1.90000000
  TIME INCREMENT  1.00000000D-01
  LEVY'S EXPLICIT METHOD WILL BE USED WITH A TIME STEP    1 TIMES
  LARGER THAN THAT USED IN THE STANDARD TRANSIENT TECHNIQUE.
  INITIAL TIME  0.00000000D-01
  FINAL TIME  7.20000000D+02
```

PAGE · 2

SUMMARY OF REGION DATA

NUMBERS AND FCN NUMBER				DIMENSIONS						BOUNDARY NUMBERS					
REG. NO.	MATL NO.	INIT TEMP	HEAT GEN.	LEFT-X-OR INNER-R	RIGHT-X-OR OUTER-R	LOWER-Y-OR LEFT-THETA	UPPER-Y-OR RIGHT-THETA	REAR-Z	FRONT-Z	LF-X IN-R	RT-X OT-R	LO-Y LF-O	UP-Y RT-O	RR-Z	FT-Z
1	1	1	0	0.0000	0.0032	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
2	2	1	1	0.0032	0.0116	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
3	1	1	0	0.0116	0.0118	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
4	2	1	1	0.0118	0.0168	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
5	1	1	0	0.0168	0.0170	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
6	3	.1	0	0.0170	0.0180	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
7	1	1	0	0.0180	0.0182	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
8	4	1	0	0.0182	0.0187	0.0000	3.1416	0.0000	0.0000	0	1	0	0	0	0

********** SUMMARY OF MATERIAL DATA **********

MATERIAL NUMBER	MATERIAL NAME	THERMAL PARAMETERS -- TEMPERATURE-DEPENDENT FUNCTION NUMBERS -- CONDUCTIVITY	DENSITY	SPECIFIC HEAT
1	HEVOID	0.0000000D-01	0.0000000D-01	5.1920000D+03
		-6	-7	0
2	FUEL	2.4000000D+01	3.5500000D+03	0.0000000D-01
		0	0	-1
3	NBCUP	0.0000000D-01	8.5700000D+03	2.7000000D+02
		-5	0	0
4	SS	0.0000000D-01	7.9500000D+03	5.0200000D+02
		-2	0	0

********** SUMMARY OF INITIAL TEMPERATURE DATA **********

NUMBER	INITIAL TEMPERATURE	POSITION-DEPENDENT FUNCTION NUMBERS X OR R	Y OR TH	Z
1	2.340000D+01	0	0	0

***************** SUMMARY OF HEAT GENERATION RATE DATA *****************

NUMBER	POWER DENSITY	TIME-, TEMPERATURE-, AND POSITION-DEPENDENT NUMBERS TIME	TEMPERATURE	X OR R	Y OR TH	Z
1	1.010600D+06	-3	0	-4	0	0

```
                                              PAGE     6
                              **********SUMMARY  OF  BOUNDARY  DATA**********

-------GENERAL------  --TEMPERATURE--  ------------------------------HEAT TRANSFER COEFFICIENTS------------------------
                        INFORMATION                                   RELATED FUNCTION NUMBERS

NO.    TYPE    FCT     TEMPERATURE              FORCED CONV.   RADIATION      NATURAL CONV   EXPONENT       FLUX
               FLAG    & TIME FCT      ASSOC.
                                       FCTS

 1      1       2      1.000000+00              1.000000+00    0.00000D-01    0.000000-01    0.00000D-01    0.00000D-01
                             -8        TIME     0              0              0              0              0
                                       TEMP     1              0              0              0              0

GROSS LATTICES AND NUMBERS OF INCREMENTS

          R OR X
          0.000000    0.003180    0.011430    0.011810    0.016760    0.016967    0.017963    0.018160
          0.018670
                 2           4           1           4           1           1           1           1

          THETA OR Y
          0.000000    3.141593
                 1

                                 LISTING  OF  ANALYTIC  FUNCTIONS

  F(V)= A(1) + A(2)*V + A(3)*V**2 + A(4)*COS(A(5)*V) + A(6)*EXP(A(7)*V) + A(8)*SIN(A(9)*V) + A(10)*LOG(A(11)*V)

NO.         A(1)       A(2)       A(3)       A(4)       A(5)       A(6)       A(7)       A(8)       A(9)       A(10)      A(11)
 1      0.0000-01  1.0000+00  2.7980-01  0.0000-01  0.0000-01  0.0000-01  0.0000-01  0.0000-01  0.0000-01  0.0000-01  0.0000-01
```

LISTING OF TABULAR FUNCTIONS

TABLE NUMBER 1 NUMBER OF PAIRS - 25

ARGUMENT	VALUE
1.00000000D+01	8.36800000D+02
5.00000000D+01	9.20480000D+02
1.00000000D+02	9.62320000D+02
2.00000000D+02	1.04600000D+03
3.00000000D+02	1.14362660D+03
4.00000000D+02	1.20290000D+03
5.00000000D+02	1.26356800D+03
6.00000000D+02	1.31098660D+03
7.00000000D+02	1.35083420D+03
8.00000000D+02	1.38595000D+03
9.00000000D+02	1.41791110D+03
1.00000000D+03	1.44766400D+03
1.10000000D+03	1.47200720D+03
1.20000000D+03	1.49578000D+03
1.30000000D+03	1.51911380D+03
1.40000000D+03	1.54210280D+03
1.50000000D+03	1.56202660D+03
1.60000000D+03	1.58469000D+03
1.70000000D+03	1.60468700D+03
1.80000000D+03	1.62478660D+03
1.90000000D+03	1.64497260D+03
2.00000000D+03	1.63140000D+03
2.10000000D+03	1.68156950D+03
2.20000000D+03	1.70022540D+03
2.31000000D+03	1.72069260D·03

TABLE NUMBER 2 NUMBER OF PAIRS - 4

ARGUMENT	VALUE
2.00000000D+01	1.73000000D+01
1.00000000D+02	1.73000000D+01
2.00000000D+02	1.73000000D+01
3.00000000D+02	1.90000000D+01

TABLE NUMBER 3 NUMBER OF PAIRS - 3

ARGUMENT	VALUE
0.00000000D-01	1.00000000D+00
1.00000000D+01	2.00000000D+01
6.00000000D+01	2.00000000D+01

TABLE NUMBER 4 NUMBER OF PAIRS - 11

ARGUMENT	VALUE
3.18000000D-03	8.10000000D-01
4.00000000D-03	8.20000000D-01
6.00000000D-03	8.40000000D-01
8.00000000D-03	8.60000000D-01
1.00000000D-02	9.20000000D-01
1.14300000D-02	9.80000000D-01
1.18100000D-02	1.00000000D+00
1.20000000D-02	1.00000000D+00
1.40000000D-02	1.10000000D+00
1.60000000D-02	1.24000000D+00

1.700000000-02 1.280000000+00

TABLE NUMBER 5 NUMBER OF PAIRS - 6

ARGUMENT	VALUE
0.000000000-01	5.230000000+01
1.000000000+02	5.440000000+01
2.000000000+02	5.650000000+01
3.000000000+02	5.860000000+01
4.000000000+02	6.070000000+01
1.000000000+03	7.270000000+01

TABLE NUMBER 6 NUMBER OF PAIRS - 18

ARGUMENT	VALUE
2.000000000+01	7.200000000-02
1.000000000+02	7.200000000-02
2.000000000+02	1.150000000-01
3.000000000+02	1.510000000-01
4.000000000+02	1.840000000-01
5.000000000+02	2.180000000-01
6.000000000+02	2.500000000-01
7.000000000+02	2.780000000-01
8.000000000+02	3.040000000-01
9.000000000+02	3.300000000-01
1.000000000+03	3.540000000-01
1.200000000+03	4.050000000-04
1.400000000+03	4.550000000-04
1.600000000+03	5.020000000-04
1.800000000+03	5.430000000-04
2.000000000+03	5.790000000-01
2.500000000+03	6.570000000-01
3.000000000+03	7.450000000-01

TABLE NUMBER 7 NUMBER OF PAIRS - 3

ARGUMENT	VALUE
2.000000000+01	3.282800000-01
1.200000000+03	1.633400000-01
2.600000000+03	1.675320000-01

TABLE NUMBER 8 NUMBER OF PAIRS - 3

ARGUMENT	VALUE
0.000000000-01	2.340000000+01
4.800000000+02	4.090000000+01
7.200000000+02	4.090000000+01

TABLE OF OUTPUT TIMES

OUTPUT NO.	OUTPUT TIME	OUTPUT NO.	OUTPUT TIME	OUTPUT NO.	OUTPUT TIME	OUTPUT NO.	OUTPUT TIME
1	0.000000-01						
2	5.000000+00						
3	1.000000+01						
4	2.000000+01						
5	3.000000+01						
6	6.000000+01						
7	1.200000+02						
8	1.800000+02						

9	2.400000+02
10	3.000000+02

11	3.600000+02
12	4.200000+02
13	4.800000+02
14	5.400000+02
15	6.000000+02
16	6.600000+02
17	7.200000+02

TEMPERATURES OF THE FOLLOWING NODES WILL BE MONITORED
EVERY 1000 ITERATIONS OR TIME STEPS.

NUMBER	NODE
1	1

FINE LATTICE, X OR R, Y OR THETA, AND Z

2	0.001590	3	0.003180	4	0.005242	5	0.007305	6	0.009367
7	0.011430	8	0.011810	9	0.013048	10	0.014285	11	0.015523
12	0.016760	13	0.016967	14	0.017963	15	0.018160	16	0.018670

1	0.000000	2	3.141593

THIS PROBLEM CONTAINS 30 NODES.

PAGE 9

STABILITY CRITERION FOR EACH NODE

1	3.72680-02	2	2.30890-01	3	2.67890-01	4	2.69910-01	5	2.70760-01	6	2.79510-01
7	9.45650-02	8	9.78620-02	9	9.78770-02	10	9.78880-02	11	9.79460-02	12	2.13000-02
13	2.18990-02	14	2.94840-02	15	3.00480-02	16	3.72680-02	17	2.30890-01	18	2.67890-01
19	2.69910-01	20	2.70760-01	21	2.79510-01	22	9.45650-02	23	9.78620-02	24	9.78770-02
25	9.78880-02	26	9.79460-02	27	2.13000-02	28	2.18990-02	29	2.94840-02	30	3.00480-02

THE STABILITY CRITERION IS 2.13000490-02 FOR POINT 12

THE INPUT TIME INCREMENT DOES NOT SATISFY THE STABILITY CRITERION.
THE TIME INCREMENT IS NOW = 2.13000490-02

```
CURRENT TIME = 19:41:58.97
HEATINGS                    ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                IBM PC
                                                  MAP OF THE NODE NUMBERS
GROSS GRID         1                 2                                 3        4                                 5        6
                   I                 I                                 I        I                                 I        I
  FINE GRID        1        2        3        4        5        6      7        8        9       10       11      12       13
    DISTANCE     0.00     0.00     0.00     0.01     0.01     0.01   0.01     0.01     0.01     0.01     0.02    0.02     0.02
                   I-----------------I---------------------------------I--------I---------------------------------I--------I--
 1   1     0.00   0I        1       2I        3        4        5     6I       7I        8        9       10     11I      12I
 2   2     3.14   0I-------16-------17I-------18-------19-------20----21I-----22I------23-------24-------25-----26I-----27I--


GROSS GRID        7        8        9
                  I        I        I
  FINE GRID      14       15       16
    DISTANCE    0.02     0.02     0.02
             -------------I--------I
 1   1     0.00  13I      14I      15I
 2   2     3.14 ---28I------29I------30I
```

```
CURRENT TIME = 19:41:59.35
HEATINGS                   ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                 IBM PC
                         STEADY STATE TEMPERATURE DISTRIBUTION  AFTER    0 ITERATIONS, TIME = 0.000000-01
GROSS GRID          1              2                               3       4                               5       6
                    I              I                               I       I                               I       I
  FINE GRID         1      2       3       4       5       6       7       8       9       10      11      12      13
      DISTANCE    0.00    0.00    0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                  I--------------I-------------------------------I-------I-------------------------------I-------I--
 1  1     0.00    0.00   23.40   23.40   23.40   23.40   23.40   23.40   23.40   23.40   23.40   23.40   23.40   23.40
 2  2     3.14    0.00----23.40----23.40----23.40----23.40----23.40----23.40----23.40----23.40----23.40----23.40----23.40----23.40


GROSS GRID          7       8       9
                    I       I       I
  FINE GRID        14      15      16
      DISTANCE    0.02    0.02    0.02
                -------------I-------I
 1  1     0.00   23.40   23.40   23.40
 2  2     3.14 ---23.40----23.40----23.40

                         TEMPERATURES ON NUMBERED BOUNDARIES

                       BOUNDARY NUMBER     TEMPERATURE
                              1             23.400000

    THE  MAXIMUM  TEMPERATURE  IS -  2.340000+01       (+-0.1)

    MAX. TEMP. APPEARS AT NODES    -          1        2        3        4        5
                                              6        7        8        9       10
                                             11       12       13       14       15
                                             16       17       18       19       20
                                             21       22       23       24       25
                                             26       27       28       29       30

    THE  MINIMUM  TEMPERATURE  IS -  2.340000+01       (+-0.1)

    MIN. TEMP. APPEARS AT NODES    -          1        2        3        4        5
                                              6        7        8        9       10
                                             11       12       13       14       15
                                             16       17       18       19       20
                                             21       22       23       24       25
                                             26       27       28       29       30
```

BEGIN THE STEADY STATE CALCULATIONS

NUMBER OF ITERATIONS	CONVERGENCE	NODE	TEMPERATURE	EXTRAPOLATION FACTOR
5	5.66246E-02	17	2.60849E+01	-3.23285E+00
10	6.25252E-02	16	3.18183E+01	-3.90536E+00
15	3.96553E-02	1	3.71002E+01	-9.96732E+00
20	2.50859E-02	2	4.31600E+01	9.99465E+00
25	2.03142E-02	1	4.75958E+01	3.12390E+01
30	1.61869E-02	16	5.24227E+01	1.74366E+01
35	1.36271E-02	1	5.59137E+01	-1.52275E+03
40	1.17513E-02	7	4.71484E+01	9.52244E+01
			BETA REDUCED TO	1.800
45	8.15575E-03	1	6.22047E+01	2.35864E+01
50	5.60954E-03	1	6.38669E+01	4.88983E+00
55	4.73064E-03	16	6.55641E+01	6.80241E+00
60	4.42279E-03	16	6.70465E+01	-9.22930E+01
			BETA REDUCED TO	1.700
65	3.35782E-03	1	6.81318E+01	4.23991E+01
70	2.64900E-03	1	6.90022E+01	1.34570E+01
75	2.39545E-03	2	6.99502E+01	2.22192E+01
80	2.29344E-03	1	7.06708E+01	2.23024E+02
			BETA REDUCED TO	1.600
85	1.83349E-03	1	7.13708E+01	5.27337E+01
90	1.55575E-03	1	7.19151E+01	4.20859E+01
95	1.46969E-03	2	7.25212E+01	6.55720E+01
100	1.42593E-03	1	7.29787E+01	1.94763E+02
			BETA REDUCED TO	1.500
105	1.16887E-03	1	7.34332E+01	8.27407E+01
110	1.03338E-03	1	7.38092E+01	2.34198E+02
115	1.00008E-03	1	7.41826E+01	1.96929E+02
120	9.80431E-04	7	5.88274E+01	3.10772E+02
			EXTRAPOLATION	
125	-6.08527E-04	14	4.15969E+01	1.44736E+01
130	-3.99778E-04	14	4.14978E+01	1.12686E+01
135	-2.64586E-04	14	4.14327E+01	1.17998E+01
140	-1.78691E-04	14	4.13892E+01	1.25137E+01
			EXTRAPOLATION	
145	-6.11265E-05	1	9.67881E+01	5.47377E+01
150	-5.59341E-05	1	9.67601E+01	5.63966E+01
155	-5.13548E-05	1	9.67344E+01	5.89335E+01
160	-4.73409E-05	1	9.67107E+01	6.20495E+01
			EXTRAPOLATION	
165	-3.06671E-05	7	7.66169E+01	4.54430E+01
170	-2.77318E-05	7	7.66059E+01	5.17840E+01
175	-2.53817E-05	7	7.65958E+01	5.88232E+01
180	-2.34724E-05	7	7.65865E+01	6.65736E+01
			EXTRAPOLATION	
185	-2.49822E-05	27	5.74217E+01	2.74105E+01
190	-2.12351E-05	27	5.74152E+01	3.23782E+01
195	-1.85039E-05	27	5.74096E+01	3.83440E+01
200	-1.67264E-05	1	9.63336E+01	6.97754E+01
			EXTRAPOLATION	
205	-1.78555E-05	22	7.64185E+01	3.75860E+01
210	-1.58036E-05	22	7.64121E+01	4.24878E+01
215	-1.41834E-05	22	7.64065E+01	4.80117E+01
220	-1.28868E-05	22	7.64014E+01	5.42238E+01
			EXTRAPOLATION	
225	-1.35062E-05	27	5.73301E+01	2.73091E+01

230	-1.14788E-05	27	5.73266E+01	3.24346E+01

235	-1.00085E-05	27	5.73236E+01	3.86096E+01

```
CURRENT TIME = 19:42:18.63
HEATINGS                        ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                      IBM PC
                              STEADY STATE TEMPERATURE DISTRIBUTION  AFTER  236 ITERATIONS, TIME = 0.00000D-01
GROSS GRID            1               2                                     3       4                                     5       6
                      1               I                                     I       I                                     I       I
   FINE GRID          1       2       3       4       5       6       7       8       9       10      11      12      13
      DISTANCE      0.00    0.00    0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                    I---------------I-------------------------------I-------I-------------------------------I-------I--
 1  1     0.00      0.00   96.18   96.18   96.13   96.00   95.79   95.52   76.35   76.15   75.91   75.65   75.34   57.32
 2  2     3.14      0.00----96.18----96.18----96.13----96.00----95.79----95.51----76.35----76.15----75.91----75.65----75.34----57.32


GROSS GRID            7       8       9
                      I       I       I
   FINE GRID         14      15      16
      DISTANCE      0.02    0.02    0.02
                  -------------I-------I
 1  1     0.00     57.21   41.17   41.00
 2  2     3.14 ---57.21----41.17----41.01

                         TEMPERATURES ON NUMBERED BOUNDARIES

                       BOUNDARY NUMBER     TEMPERATURE
                              1             23.400000

    THE  MAXIMUM  TEMPERATURE  IS -  9.617830+01       (+-0.1)

    MAX. TEMP. APPEARS AT NODES   -          1         2         3         16        17
                                            18

    THE  MINIMUM  TEMPERATURE  IS -  4.100480+01       (+-0.1)

    MIN. TEMP. APPEARS AT NODES   -          15        30

         THE STEADY STATE CALCULATIONS HAVE BEEN COMPLETED.

         NUMBER OF ITERATIONS COMPLETED =   236
```

```
CURRENT TIME = 19:42:19.18
HEATINGS                    ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                          IBM PC
                            TRANSIENT TEMPERATURE DISTRIBUTION  AFTER    1 TIME STEPS, TIME = 2.10186D-02
GROSS GRID          1                 2                                       3        4                                       5        6
                    I                 I                                       I        I                                       I        I
  FINE GRID         1        2        3        4        5        6        7        8        9        10       11       12       13
     DISTANCE       0.00     0.00     0.00     0.01     0.01     0.01     0.01     0.01     0.01     0.01     0.02     0.02     0.02
                    I-----------------I---------------------------------I--------I----------------------------------I--------I--
 1  1     0.00      0.00     96.18    96.18    96.13    96.00    95.79    95.52    76.35    76.15    75.91    75.65    75.34    57.32
 2  2     3.14      0.00----96.18----96.18----96.13----96.00----95.79----95.51----76.35----76.15----75.91----75.65----75.34----57.32


GROSS GRID          7        8        9
                    I        I        I
  FINE GRID         14       15       16
     DISTANCE       0.02     0.02     0.02
                --------------I--------I
 1  1     0.00      57.21    41.17    41.00
 2  2     3.14  ---57.21----41.17----41.01

                        TEMPERATURES ON NUMBERED BOUNDARIES

                        BOUNDARY NUMBER     TEMPERATURE
                              1               23.400766

                  THE CURRENT TIME STEP (DELTAT) = 2.101862660-02

   THE  MAXIMUM  TEMPERATURE  IS -  9.617800D+01       (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -          1          2          3          16          17
                                            18

   THE  MINIMUM  TEMPERATURE  IS -  4.100480D+01       (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -          15         30
```

```
CURRENT TIME = 19:42:46.70
HEATINGS                     ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                         IBM PC
                            TRANSIENT TEMPERATURE DISTRIBUTION  AFTER  238 TIME STEPS, TIME = 5.00172D+00
GROSS GRID          1                 2                                   3        4                                     5        6
                    I                 I                                   I        I                                     I        I
  FINE GRID         1        2        3        4        5        6        7        8        9        10       11       12       13
      DISTANCE      0.00     0.00     0.00     0.01     0.01     0.01     0.01     0.01     0.01     0.01     0.02     0.02     0.02
                    I-----------------I-----------------------------------I--------I-------------------------------------I--------I--
 1  1     0.00      0.00     102.17   102.28   102.28   102.24   102.16   101.98   84.17    84.01    83.83    83.58    83.22    58.72
 2  2     3.14      0.00---102.17---102.28---102.28---102.24---102.16---101.98----84.17----84.01----83.82----83.58----83.22----58.72


GROSS GRID          7        8        9
                    I        I        I
  FINE GRID         14       15       16
      DISTANCE      0.02     0.02     0.02
                ---------------I--------I
 1  1     0.00      58.59    41.41    41.24
 2  2     3.14  ---58.59----41.41----41.24

                             TEMPERATURES ON NUMBERED BOUNDARIES

                           BOUNDARY NUMBER      TEMPERATURE
                                 1                23.582354

                         THE CURRENT TIME STEP (DELTAT) = 2.100738600-02

   THE  MAXIMUM  TEMPERATURE  IS -  1.022790+02        (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -          2          3          4          17          18
                                            19

   THE  MINIMUM  TEMPERATURE  IS -  4.123690+01        (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -          15         30
```

```
CURRENT TIME = 19:43:14.55
HEATINGS                        ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                    IBM PC
                                 TRANSIENT TEMPERATURE DISTRIBUTION  AFTER  476 TIME STEPS, TIME = 9.99572D+00
GROSS GRID           1                2                                    3         4                                       5         6
                     I                I                                    I         I                                       I         I
  FINE GRID          1       2        3        4        5        6         7         8        9        10       11       12        13
     DISTANCE      0.00    0.00     0.00     0.01     0.01     0.01      0.01      0.01     0.01     0.01     0.02     0.02      0.02
                   I----------------I--------------------------------I--------I--------------------------------I--------I--
 1  1     0.00     0.00   120.61   120.80   120.86   120.96   121.04   120.97   106.73   106.59   106.40   106.08   105.52    65.82
 2  2     3.14     0.00---120.61---120.80---120.86---120.96---121.04---120.97---106.73---106.59---106.40---106.08---105.52----65.82


GROSS GRID           7       8       9
                     I       I       I
  FINE GRID         14      15      16
     DISTANCE      0.02    0.02    0.02
                -------------I--------I
 1  1     0.00    65.62   43.28   43.06
 2  2     3.14 ---65.62----43.28----43.06

                          TEMPERATURES ON NUMBERED BOUNDARIES

                        BOUNDARY NUMBER      TEMPERATURE
                               1               23.764427

                      THE CURRENT TIME STEP (DELTAT) = 2.09499104D-02

   THE  MAXIMUM  TEMPERATURE  IS -  1.20956D+02        (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -          4         5         6         18         19
                                           20        21

   THE  MINIMUM  TEMPERATURE  IS -  4.30601D+01        (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -         15        30
```

```
 CURRENT TIME = 19:44:10.51
HEATINGS                  ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                IBM PC
                          TRANSIENT TEMPERATURE DISTRIBUTION  AFTER  956 TIME STEPS, TIME = 1.99950D+01
GROSS GRID          1           2                             3       4                             5       6
                    I           I                             I       I                             I       I
  FINE GRID         1     2     3       4       5       6     7       8       9       10      11    12      13
     DISTANCE    0.00  0.00  0.00    0.01    0.01    0.01  0.01    0.01    0.01    0.01    0.02  0.02    0.02
                 I---------------I-------------------------------I--------I-------------------------------I--------I--
 1  1     0.00   0.00  169.56  169.70  169.78  169.92  170.06  170.04  160.52  160.32  159.90  159.21  158.13  95.86
 2  2     3.14   0.00---169.55---169.70---169.78---169.92---170.06---170.04---160.52---160.32---159.90---159.21---158.13----95.86


GROSS GRID         7       8       9
                   I       I       I
  FINE GRID        14      15      16
     DISTANCE    0.02    0.02    0.02
               -------------I--------I
 1  1     0.00   95.49   52.96   52.54
 2  2     3.14 ---95.49----52.96----52.54
```

TEMPERATURES ON NUMBERED BOUNDARIES

BOUNDARY NUMBER	TEMPERATURE
1	24.128984

THE CURRENT TIME STEP (DELTAT) = 2.068856760-02

THE MAXIMUM TEMPERATURE IS - 1.700590+02 (+-0.1)

MAX. TEMP. APPEARS AT NODES - 5 6 20 21

THE MINIMUM TEMPERATURE IS - 5.254240+01 (+-0.1)

MIN. TEMP. APPEARS AT NODES - 15 30

TABLE FOR SPECIAL MONITORING OF TEMPERATURES

NUMBER OF TIME STEPS	TIME	==================== NODE NUMBERS AND TEMPERATURES ====================
1000	2.09050+01	1 1.739240+02

```
                                                   PAGE   19

 CURRENT TIME = 1\      7.64
HEATINGS                          ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                        IBM PC
                                 TRANSIENT TEMPERATURE DISTRIBUTION  AFTER 1443 TIME STEPS, TIME = 2.99942D+01
GROSS GRID           1                 2                                 3        4                                 5         6
                     I                 I                                 I        I                                 I         I
  FINE GRID          1       2         3       4       5       6         7        8       9       10      11       12        13
       DISTANCE    0.00    0.00      0.00    0.01    0.01    0.01      0.01     0.01    0.01    0.01    0.02     0.02      0.02
                   I-----------------I---------------------------------I--------I---------------------------------I---------I--
 1  1      0.00    0.00  216.59    216.70  216.77  216.88  216.96    216.87   205.57  205.26  204.62  203.59   202.07    131.27
 2  2      3.14    0.00---216.59---216.70---216.77---216.88---216.96---216.87---205.57---205.26---204.62---203.59---202.07---131.27


GROSS GRID           7       8       9
                     I       I       I
  FINE GRID         14      15      16
       DISTANCE    0.02    0.02    0.02
                 --------------I--------I
 1  1      0.00  130.74   63.42   62.74
 2  2      3.14 --130.74----63.42----62.74

                            TEMPERATURES ON NUMBERED BOUNDARIES

                          BOUNDARY NUMBER      TEMPERATURE
                                 1               24.493540

                        THE CURRENT TIME STEP (DELTAT) = 2.03578314D-02

    THE  MAXIMUM  TEMPERATURE  IS -  2.16880D+02       (+-0.1)

    MAX. TEMP. APPEARS AT NODES   -          4          5          6          19          20
                                            21

    THE  MINIMUM  TEMPERATURE  IS -  6.27351D+01       (+-0.1)

    MIN. TEMP. APPEARS AT NODES   -          15         30

                                                   TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF      TIME      ====================================== NODE NUMBERS AND TEMPERATURES ======================================
TIME STEPS
  2000      4.04720+01     1 2.630630+02
  3000      5.63490+01     1 3.272840+02
```

```
                                        PAGE    20

CURRENT TIME = 19:48:41.63
HEATINGS                         ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                  IBM PC
                                 TRANSIENT TEMPERATURE DISTRIBUTION  AFTER 3255 TIME STEPS, TIME = 6.00069D+01
GROSS GRID          1               2                                       3         4                                         5         6
                    I               I                                       I         I                                         I         I
  FINE GRID         1       2       3       4       5       6       7       8       9       10      11      12      13
      DISTANCE      0.00    0.00    0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                    I---------------I---------------------------------------I---------I-----------------------------------------I---------I--
1  1     0.00       0.00    341.05  341.11  341.04  340.77  340.26  339.37  305.84  304.87  303.36  301.23  298.41  202.57
2  2     3.14       0.00---341.05---341.11---341.04---340.77---340.26---339.37---305.84---304.87---303.36---301.23---298.41---202.57


GROSS GRID          7       8       9
                    I       I       I
  FINE GRID         14      15      16
      DISTANCE      0.02    0.02    0.02
                ------------I-------I
1  1     0.00   201.56  84.82   83.29
2  2     3.14 --201.56----84.82----83.29

                          TEMPERATURES ON NUMBERED BOUNDARIES

                          BOUNDARY NUMBER      TEMPERATURE
                                1                25.587751

                          THE CURRENT TIME STEP (DELTAT) = 1.409947260-02

   THE  MAXIMUM  TEMPERATURE  IS -  3.410520+02        (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -          1          2          3          16          17
                                            18

   THE  MINIMUM  TEMPERATURE  IS -  8.328510+01        (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -          15         30

***** TABLE  3 MUST BE EVALUATED FOR  6.000687940+01
      THE VALUE OF THE FUNCTION WILL BE  2.000000000+01 FOR ALL ARGUMENTS GREATER THAN  6.000000000+01

                                              TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF      TIME     ==================================== NODE NUMBERS AND TEMPERATURES ====================================
TIME STEPS
  4000      7.00490+01    1 3.768470+02
  5000      8.23680+01    1 4.166850+02
  6000      9.37010+01    1 4.494610+02
  7000      1.04300+02    1 4.769410+02
  8000      1.14340+02    1 5.003350+02
```

```
CURRENT TIME = 19:59:20.90
HEATINGS                    ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                 IBM PC
                           TRANSIENT TEMPERATURE DISTRIBUTION  AFTER 8584 TIME STEPS, TIME = 1.19998D+02
GROSS GRID          1              2                                   3       4                                 5        6
                    I              I                                   I       I                                 I        I
   FINE GRID        1       2      3       4       5       6       7       8       9      10      11      12      13
       DISTANCE   0.00    0.00   0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                    I--------------I-----------------------------------I-------I---------------------------------I--------I--
 1   1     0.00   0.00  512.47  512.49  511.95  510.48  508.13  504.80  421.23  418.60  415.28  411.19  406.25  275.73
 2   2     3.14   0.00---512.47---512.49---511.95---510.48---508.13---504.80---421.23---418.60---415.28---411.19---406.25---275.73


GROSS GRID          7       8       9
                    I       I       I
   FINE GRID       14      15      16
       DISTANCE   0.02    0.02    0.02
               -------------I-------I
 1   1     0.00  274.02  104.47  101.73
 2   2     3.14 --274.02---104.47---101.73

                      TEMPERATURES ON NUMBERED BOUNDARIES

                        BOUNDARY NUMBER      TEMPERATURE
                              1               27.774930

                   THE CURRENT TIME STEP (DELTAT) = 9.56693867D-03

    THE  MAXIMUM  TEMPERATURE  IS -  5.12469D+02        (+-0.1)

    MAX. TEMP. APPEARS AT NODES   -          1          2          16          17

    THE  MINIMUM  TEMPERATURE  IS -  1.01727D+02        (+-0.1)

    MIN. TEMP. APPEARS AT NODES   -          15         30

                                         TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF     TIME      ======================================= NODE NUMBERS AND TEMPERATURES ========================================
TIME STEPS
   9000     1.2395D+02    1 5.20527D+02
  10000     1.3320D+02    1 5.38147D+02
  11000     1.4216D+02    1 5.53632D+02
  12000     1.5087D+02    1 5.67325D+02
  13000     1.5938D+02    1 5.79506D+02
  14000     1.6770D+02    1 5.90395D+02
  15000     1.7584D+02    1 6.00167D+02
```

```
CURRENT TIME = 20:13:23.41
HEATINGS                        ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                IBM ?C
                                TRANSIENT TEMPERATURE DISTRIBUTION  AFTER15513 TIME STEPS, TIME = 1.79997D+02
GROSS GRID          1                 2                                       3        4                                      5        6
                    I                 I                                       I        I                                      I        I
  FINE GRID         1        2        3        4        5        6        7        8        9        10       11       12       13
     DISTANCE     0.00     0.00     0.00     0.01     0.01     0.01     0.01     0.01     0.01     0.01     0.02     0.02     0.02
                  I-----------------I---------------------------------I--------I-----------------------------------I--------I--
1  1    0.00      0.00   604.80   604.81   603.93   601.60   597.95   592.91   482.19   478.43   473.91   468.58   462.34   313.42
2  2    3.14      0.00---604.80---604.81---603.93---601.60---597.95---592.91---482.19---478.43---473.91---468.58---462.34---313.42


GROSS GRID          7        8        9
                    I        I        I
  FINE GRID        14       15       16
     DISTANCE     0.02     0.02     0.02
                -------------I--------I
1  1    0.00    311.31   113.65   110.19
2  2    3.14 --311.31---113.65---110.19

                         TEMPERATURES ON NUMBERED BOUNDARIES

                       BOUNDARY NUMBER      TEMPERATURE
                              1               29.962401

                    THE CURRENT TIME STEP (DELTAT) = 8.02922739D-03

    THE  MAXIMUM  TEMPERATURE  IS -  6.04797D+02      (+-0.1)

    MAX. TEMP. APPEARS AT NODES  -          1         2         16         17

    THE  MINIMUM  TEMPERATURE  IS -  1.10188D+02      (+-0.1)

    MIN. TEMP. APPEARS AT NODES  -         15        30

                                              TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF    TIME     ======================================== NODE NUMBERS AND TEMPERATURES ========================================
TIME STEPS
 16000     1.8389D+02    1 6.08974D+02
 17000     1.9181D+02    1 6.16938D+02
 18000     1.9963D+02    1 6.24158D+02
 19000     2.0736D+02    1 6.30715D+02
 20000     2.1501D+02    1 6.36682D+02
 21000     2.2259D+02    1 6.42118D+02
 22000     2.3011D+02    1 6.47078D+02
 23000     2.3756D+02    1 6.51609D+02
```

```
CURRENT TIME = 20:29:21.58
HEATING5                       ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                    IBM PC
                              TRANSIENT TEMPERATURE DISTRIBUTION  AFTER23328 TIME STEPS, TIME = 2.39997D+02
GROSS GRID           1                2                                    3         4                                      5         6
                     I                I                                    I         I                                      I         I
  FINE GRID          1         2      3         4         5         6      7         8         9        10        11        12        13
     DISTANCE      0.00      0.00   0.00      0.01      0.01      0.01   0.01      0.01      0.01      0.01      0.02      0.02      0.02
                     I----------------I------------------------------------I---------I--------------------------------------I---------I--
 1  1     0.00     0.00    653.01   653.01    651.95    649.14    644.76   638.75    514.53    510.13    504.94    498.89    491.91    333.58
 2  2     3.16     0.00---653.01---653.01---651.95---649.14---644.76---638.75---514.53---510.13---504.94---498.89---491.91---333.58


GROSS GRID           7        8        9
                     I        I        I
  FINE GRID         14       15       16
     DISTANCE      0.02     0.02     0.02
               -------------I--------I
 1  1     0.00   331.25   118.27   114.39
 2  2     3.16 --331.25---118.27---114.39

                         TEMPERATURES ON NUMBERED BOUNDARIES

                        BOUNDARY NUMBER      TEMPERATURE
                               1               32.149880

                    THE CURRENT TIME STEP (DELTAT) = 7.41163578D-03

   THE  MAXIMUM  TEMPERATURE  IS -  6.53009D+02        (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -          1          2         16         17

   THE  MINIMUM  TEMPERATURE  IS -  1.14395D+02        (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -         15         30

                                             TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF     TIME     ======================================== NODE NUMBERS AND TEMPERATURES ========================================
TIME STEPS
 24000     2.44970+02     1 6.557530+02
 25000     2.52320+02     1 6.595460+02
 26000     2.59630+02     1 6.630220+02
 27000     2.66900+02     1 6.662090+02
 28000     2.74140+02     1 6.691340+02
 29000     2.81340+02     1 6.718210+02
 30000     2.88520+02     1 6.742890+02
 31000     2.95660+02     1 6.765590+02
```

```
 CURRENT TIME = 20:46:19.79
HEATINGS                         ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                    IBM PC
                                TRANSIENT TEMPERATURE DISTRIBUTION  AFTER31609 TIME STEPS, TIME = 3.00000D+02
GROSS GRID          1              2                                     3       4                                    5       6
                    I              I                                     I       I                                    I       I
   FINE GRID        1       2      3       4       5       6       7       8       9      10      11      12      13
       DISTANCE   0.00    0.00   0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                  I--------------I-------------------------------I-------I-------------------------------I-------I--
 1  1     0.00    0.00  677.85  677.85  676.69  673.62  668.84  662.32  531.28  526.54  520.99  514.56  507.19  344.02
 2  2     3.14    0.00---677.85---677.85---676.69---673.62---668.84---662.32---531.28---526.54---520.99---514.56---507.19---344.02


GROSS GRID          7       8       9
                    I       I       I
   FINE GRID       14      15      16
       DISTANCE   0.02    0.02    0.02
                --------------I--------I
 1  1     0.00  341.57  120.60  116.50
 2  2     3.14 --341.57---120.60---116.50

                        TEMPERATURES ON NUMBERED BOUNDARIES

                          BOUNDARY NUMBER      TEMPERATURE
                                1               34.337518

                     THE CURRENT TIME STEP (DELTAT) = 7.11736014D-03

    THE  MAXIMUM  TEMPERATURE  IS -  6.77851D+02      (+-0.1)

    MAX. TEMP. APPEARS AT NODES   -         1         2        16        17

    THE  MINIMUM  TEMPERATURE  IS -  1.16502D+02      (+-0.1)

    MIN. TEMP. APPEARS AT NODES   -        15        30

                                          TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF     TIME     ====================================== NODE NUMBERS AND TEMPERATURES ======================================
TIME STEPS
 32000     3.0278D+02    1 6.78647D+02
 33000     3.0988D+02    1 6.80569D+02
 34000     3.1695D+02    1 6.82338D+02
 35000     3.2401D+02    1 6.83971D+02
 36000     3.3105D+02    1 6.85478D+02
 37000     3.3807D+02    1 6.86871D+02
 38000     3.4508D+02    1 6.88157D+02
 39000     3.5207D+02    1 6.89345D+02
 40000     3.5905D+02    1 6.90442D+02
```

```
CURRENT TIME = 21: 3:49.31
HEATINGS                       ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                IBM PC
                               TRANSIENT TEMPERATURE DISTRIBUTION  AFTER40136 TIME STEPS, TIME = 3.59999D+02
GROSS GRID          1               2                                   3       4                                 5        6
                    I               I                                   I       I                                 I        I
  FINE GRID         1       2       3       4       5       6           7       8       9       10      11       12       13
     DISTANCE     0.00    0.00    0.00    0.01    0.01    0.01        0.01    0.01    0.01    0.01    0.02     0.02     0.02
                    I---------------I-----------------------------------I-------I---------------------------------I--------I--
 1  1     0.00    0.00  690.58  690.59  689.37  686.16  681.18      674.39  539.83  534.91  529.17  522.55   514.97   349.34
 2  2     3.14    0.00---690.58---690.59---689.37---686.16---681.18---674.39---539.83---534.91---529.17---522.55---514.97---349.34


GROSS GRID          7       8       9
                    I       I       I
  FINE GRID        14      15      16
     DISTANCE     0.02    0.02    0.02
              --------------I-------I
 1  1     0.00  346.82  121.76  117.55
 2  2     3.14 --346.82---121.76---117.55

                    TEMPERATURES ON NUMBERED BOUNDARIES

                    BOUNDARY NUMBER      TEMPERATURE
                          1               36.524968

               THE CURRENT TIME STEP (DELTAT) = 6.97229149D-03

   THE  MAXIMUM  TEMPERATURE  IS -  6.90584D+02        (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -          1          2        16        17

   THE  MINIMUM  TEMPERATURE  IS -  1.17554D+02        (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -         15         30

                                      TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF     TIME     ==================================== NODE NUMBERS AND TEMPERATURES ====================================
TIME STEPS
 41000     3.6602D+02    1 6.91455D+02
 42000     3.7298D+02    1 6.92392D+02
 43000     3.7992D+02    1 6.93258D+02
 44000     3.8686D+02    1 6.94058D+02
 45000     3.9379D+02    1 6.94797D+02
 46000     4.0071D+02    1 6.95481D+02
 47000     4.0763D+02    1 6.96113D+02
 48000     4.1453D+02    1 6.96698D+02
```

```
CURRENT TIME = 21:21:34.97
HEATINGS                      ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                IBM PC
                              TRANSIENT TEMPERATURE DISTRIBUTION  AFTER48792 TIME STEPS, TIME = 6.19999D+02
GROSS GRID          1               2                                   3       4                                 5       6
                    I               I                                   I       I                                 I       I
  FINE GRID         1       2       3       4       5       6       7       8       9      10      11      12      13
     DISTANCE     0.00    0.00    0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                    I---------------I-----------------------------------I-------I---------------------------------I-------I--
 1  1    0.00     0.00  697.13  697.13  695.89  692.61  687.53  680.60  544.18  539.17  533.34  526.61  518.92  352.04
 2  2    3.14     0.00---697.13---697.13---695.89---692.61---687.53---680.60---544.18---539.17---533.34---526.61---518.92---352.04


GROSS GRID          7       8       9
                    I       I       I
  FINE GRID        14      15      16
     DISTANCE     0.02    0.02    0.02
               -------------I-------I
 1  1    0.00   349.50  122.36  118.10
 2  2    3.14 --349.50---122.36---118.10

                         TEMPERATURES ON NUMBERED BOUNDARIES

                      BOUNDARY NUMBER      TEMPERATURE
                             1              38.712445

                    THE CURRENT TIME STEP (DELTAT) = 6.899170620D-03

     THE  MAXIMUM  TEMPERATURE  IS -  6.971300D+02       (+-0.1)

     MAX. TEMP. APPEARS AT NODES   -           1          2          16          17

     THE  MINIMUM  TEMPERATURE  IS -  1.180970D+02       (+-0.1)

     MIN. TEMP. APPEARS AT NODES   -          15         30

                                            TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF     TIME     ===================================== NODE NUMBERS AND TEMPERATURES ======================================
TIME STEPS
 49000     4.2143D+02    1 6.97239D+02
 50000     4.2833D+02    1 6.97739D+02
 51000     4.3522D+02    1 6.98202D+02
 52000     4.4210D+02    1 6.98631D+02
 53000     4.4898D+02    1 6.99027D+02
 54000     4.5586D+02    1 6.99394D+02
 55000     4.6273D+02    1 6.99734D+02
 56000     4.6960D+02    1 7.00048D+02
 57000     4.7647D+02    1 7.00339D+02
```

PAGE 27

CURRENT TIME = 21:39:29.20

HEATINGS

ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec. IBM PC

TRANSIENT TEMPERATURE DISTRIBUTION AFTER57515 TIME STEPS, TIME = 4.80000D+02

GROSS GRID			1		2				3	4				5	6
FINE GRID			1	2	3	4	5	6	7	8	9	10	11	12	13
DISTANCE			0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
1	1	0.00	0.00	700.48	700.48	699.22	695.91	690.77	683.77	546.41	541.36	535.47	528.70	520.95	353.44
2	2	3.14	0.00	700.48	700.48	699.22	695.91	690.77	683.77	546.41	541.36	535.47	528.70	520.95	353.44

GROSS GRID			7	8	9
FINE GRID			14	15	16
DISTANCE			0.02	0.02	0.02
1	1	0.00	350.88	122.71	118.41
2	2	3.14	350.88	122.71	118.41

TEMPERATURES ON NUMBERED BOUNDARIES

BOUNDARY NUMBER	TEMPERATURE
1	40.900000

THE CURRENT TIME STEP (DELTAT) = 6.862347660-03

THE MAXIMUM TEMPERATURE IS - 7.004810+02 (+-0.1)

MAX. TEMP. APPEARS AT NODES - 1 2 16 17

THE MINIMUM TEMPERATURE IS - 1.184090+02 (+-0.1)

MIN. TEMP. APPEARS AT NODES - 15 30

TABLE FOR SPECIAL MONITORING OF TEMPERATURES

NUMBER OF TIME STEPS	TIME	NODE NUMBERS AND TEMPERATURES
58000	4.83330+02	1 7.006090+02
59000	4.90190+02	1 7.008590+02
60000	4.97050+02	1 7.010900+02
61000	5.03900+02	1 7.013040+02
62000	5.10750+02	1 7.015030+02
63000	5.17600+02	1 7.016840+02
64000	5.24450+02	1 7.018560+02
65000	5.31300+02	1 7.020140+02
66000	5.38140+02	1 7.021600+02

```
CURRENT TIME = 21:57:30.14
HEATINGS                    ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                IBM PC
                            TRANSIENT TEMPERATURE DISTRIBUTION  AFTER66271 TIME STEPS, TIME = 5.39999D+02
GROSS GRID          1               2                                       3       4                                       5       6
                    I               I                                       I       I                                       I       I
  FINE GRID         1       2       3       4       5       6       7       8       9       10      11      12      13
     DISTANCE     0.00    0.00    0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                    I---------------I---------------------------------------I-------I---------------------------------------I-------I--
 1  1     0.00    0.00  702.20  702.20  700.93  697.60  692.44  685.40  547.56  542.48  536.57  529.76  521.99  354.15
 2  2     3.14    0.00---702.20---702.20---700.93---697.60---692.44---685.40---547.56---542.48---536.57---529.76---521.99---354.15


GROSS GRID          7       8       9
                    I       I       I
  FINE GRID        14      15      16
     DISTANCE     0.02    0.02    0.02
              -------------I--------I
 1  1     0.00  351.58  122.86  118.55
 2  2     3.14 --351.58---122.86---118.55

                    TEMPERATURES ON NUMBERED BOUNDARIES

                    BOUNDARY NUMBER     TEMPERATURE
                          1              40.900000

                 THE CURRENT TIME STEP (DELTAT) = 6.84430221D-03

    THE  MAXIMUM  TEMPERATURE  IS -  7.02197D+02       (+-0.1)

    MAX. TEMP. APPEARS AT NODES   -          1          2          16          17

    THE  MINIMUM  TEMPERATURE  IS -  1.18553D+02       (+-0.1)

    MIN. TEMP. APPEARS AT NODES   -         15         30

                                              TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF     TIME     ====================================== NODE NUMBERS AND TEMPERATURES ======================================
TIME STEPS
 67000     5.4499D+02    1 7.02295D+02
 68000     5.5183D+02    1 7.02420D+02
 69000     5.5867D+02    1 7.02536D+02
 70000     5.6551D+02    1 7.02643D+02
 71000     5.7235D+02    1 7.02742D+02
 72000     5.7919D+02    1 7.02834D+02
 73000     5.8603D+02    1 7.02920D+02
 74000     5.9286D+02    1 7.02999D+02
 75000     5.9970D+02    1 7.03072D+02
```

```
CURRENT TIME = 22:15:32.77
HEATINGS                      ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                    IBM PC
                              TRANSIENT TEMPERATURE DISTRIBUTION  AFTER75044 TIME STEPS, TIME = 5.99999D+02
GROSS GRID          1               2                                   3       4                                   5       6
                    I               I                                   I       I                                   I       I
  FINE GRID         1       2       3       4       5       6       7       8       9       10      11      12      13
     DISTANCE     0.00    0.00    0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                    I---------------I-----------------------------------I-------I-----------------------------------I-------I--
 1  1    0.00     0.00  703.07  703.07  701.81  698.47  693.29  686.23  548.14  543.05  537.12  530.31  522.52  354.52
 2  2    3.14     0.00---703.07---703.07---701.81---698.47---693.29---686.23---548.14---543.05---537.12---530.31---522.52---354.52


GROSS GRID          7       8       9
                    I       I       I
  FINE GRID        14      15      16
     DISTANCE     0.02    0.02    0.02
                ------------I-------I
 1  1    0.00   351.94  122.95  118.63
 2  2    3.14 --351.94---122.95---118.63

                          TEMPERATURES ON NUMBERED BOUNDARIES

                        BOUNDARY NUMBER      TEMPERATURE
                               1               40.900000

                      THE CURRENT TIME STEP (DELTAT) = 6.83509924D-03

   THE  MAXIMUM  TEMPERATURE  IS -  7.03075D+02        (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -          1          2          16          17

   THE  MINIMUM  TEMPERATURE  IS -  1.18626D+02        (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -          15         30

                                           TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF     TIME     ===================================== NODE NUMBERS AND TEMPERATURES =====================================
TIME STEPS
 76000      6.0653D+02     1 7.03139D+02
 77000      6.1337D+02     1 7.03202D+02
 78000      6.2020D+02     1 7.03260D+02
 79000      6.2703D+02     1 7.03314D+02
 80000      6.3387D+02     1 7.03364D+02
 81000      6.4070D+02     1 7.03410D+02
 82000      6.4753D+02     1 7.03453D+02
 83000      6.5436D+02     1 7.03493D+02
```

```
CURRENT TIME = 22:33:36.51
HEATINGS                      ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                    IBM PC
                              TRANSIENT TEMPERATURE DISTRIBUTION  AFTER83826 TIME STEPS, TIME = 6.60002D+02
GROSS GRID          1               2                              3       4                              5       6
                    I               I                              I       I                              I       I
  FINE GRID         1       2       3       4       5       6      7       8       9      10      11     12      13
     DISTANCE    0.00    0.00    0.00    0.01    0.01    0.01   0.01    0.01    0.01    0.01    0.02   0.02    0.02
                    I---------------I------------------------------I-------I------------------------------I-------I--
 1  1     0.00   0.00  703.52  703.52  702.25  698.91  693.72  686.66  548.44  543.34  537.41  530.59  522.79  354.70
 2  2     3.14   0.00---703.52---703.52---702.25---698.91---693.72---686.66---548.44---543.34---537.41---530.59---522.79---354.70


GROSS GRID          7       8       9
                    I       I       I
  FINE GRID        14      15      16
     DISTANCE    0.02    0.02    0.02
               -------------I-------I
 1  1     0.00  352.12  122.99  118.66
 2  2     3.14 --352.12---122.99---118.66

                         TEMPERATURES ON NUMBERED BOUNDARIES

                       BOUNDARY NUMBER       TEMPERATURE
                             1                40.900000

                      THE CURRENT TIME STEP (DELTAT) = 6.83040438D-03

    THE  MAXIMUM  TEMPERATURE  IS -  7.03523D+02        (+-0.1)

    MAX. TEMP. APPEARS AT NODES   -          1          2          16          17

    THE  MINIMUM  TEMPERATURE  IS -  1.18663D+02        (+-0.1)

    MIN. TEMP. APPEARS AT NODES   -         15         30

                                              TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF     TIME     ==================================== NODE NUMBERS AND TEMPERATURES ====================================
TIME STEPS
 84000     6.6119D+02    1 7.03529D+02
 85000     6.6802D+02    1 7.03563D+02
 86000     6.7485D+02    1 7.03595D+02
 87000     6.8168D+02    1 7.03624D+02
 88000     6.8851D+02    1 7.03651D+02
 89000     6.9534D+02    1 7.03676D+02
 90000     7.0217D+02    1 7.03699D+02
 91000     7.0900D+02    1 7.03721D+02
 92000     7.1582D+02    1 7.03741D+02

***** TABLE  8 MUST BE EVALUATED FOR  7.20002511D+02
      THE VALUE OF THE FUNCTION WILL BE  4.09000000D+01 FOR ALL ARGUMENTS GREATER THAN  7.20000000D+02
```

```
CURRENT TIME = 22:51:40.74
HEATINGS                 ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                 IBM PC
                         TRANSIENT TEMPERATURE DISTRIBUTION  AFTER92612 TIME STEPS, TIME = 7.200030+02
GROSS GRID           1             2                                  3       4                                      5       6
                     I             I                                  I       I                                      I       I
  FINE GRID          1      2      3       4       5       6          7       8       9       10      11      12      13
     DISTANCE      0.00   0.00   0.00    0.01    0.01    0.01       0.01    0.01    0.01    0.01    0.02    0.02    0.02
                     I-------------I----------------------------------I-------I--------------------------------------I-------I--
 1  1     0.00     0.00  703.75  703.75  702.48  699.14  693.94     686.87  548.59  543.49  537.55  530.73  522.93  354.79
 2  2     3.14     0.00---703.75---703.75---702.48---699.14---693.94---686.87---548.59---543.49---537.55---530.73---522.93---354.79


GROSS GRID           7       8       9
                     I       I       I
  FINE GRID         14      15      16
     DISTANCE      0.02    0.02    0.02
               -------------I--------I
 1  1     0.00   352.21  123.01  118.68
 2  2     3.14 --352.21---123.01---118.68
```

TEMPERATURES ON NUMBERED BOUNDARIES

BOUNDARY NUMBER	TEMPERATURE
1	40.900000

THE CURRENT TIME STEP (DELTAT) = 6.828008520-03

THE MAXIMUM TEMPERATURE IS - 7.037520+02 (+-0.1)

MAX. TEMP. APPEARS AT NODES - 1 2 16 17

THE MINIMUM TEMPERATURE IS - 1.186820+02 (+-0.1)

MIN. TEMP. APPEARS AT NODES - 15 30

THE TRANSIENT CALCULATIONS HAVE BEEN COMPLETED.

FINAL TIME IS 7.200030+02

NUMBER OF TIME STEPS COMPLETED = 92612

BEGIN THE STEADY STATE CALCULATIONS

NUMBER OF ITERATIONS	CONVERGENCE	NODE	TEMPERATURE	EXTRAPOLATION FACTOR

```
                                              PAGE    33


 CURRENT TIME = 22:51:41.29
HEATINGS                       ACRR HEAT DEPOSITION TRANSIENT #2 - 100KW to 2MW in 10 sec.                      IBM PC
                             STEADY STATE TEMPERATURE DISTRIBUTION  AFTER    2 ITERATIONS, TIME = 7.20003D+02
GROSS GRID          1         2                             3      4                                  5      6
                    I         I                             I      I                                  I      I
  FINE GRID         1     2     3     4     5     6     7     8     9     10     11     12     13
     DISTANCE     0.00   0.00   0.00   0.01   0.01   0.01   0.01   0.01   0.01   0.01   0.02   0.02   0.02
                    I---------------I------------------------------I--------I----------------------------------I--------I--
 1  1     0.00    0.00   703.75   703.76   702.49   699.14   693.95   686.89   548.59   543.49   537.56   530.73   522.93   354.80
 2  2     3.14    0.00---703.75---703.76---702.49---699.14---693.95---686.89---548.59---543.49---537.56---530.73---522.93---354.80


GROSS GRID          7       8       9
                    I       I       I
  FINE GRID        14      15      16
     DISTANCE     0.02    0.02    0.02
                -------------I--------I
 1  1     0.00  352.21   123.01   118.68
 2  2     3.14 --352.21---123.01---118.68

                         TEMPERATURES ON NUMBERED BOUNDARIES

                       BOUNDARY NUMBER     TEMPERATURE
                              1              40.900000

   THE  MAXIMUM  TEMPERATURE  IS -  7.03754D+02       (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -          1          2         16         17

   THE  MINIMUM  TEMPERATURE  IS -  1.18682D+02       (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -         15         30

       THE STEADY STATE CALCULATIONS HAVE BEEN COMPLETED.

       NUMBER OF ITERATIONS COMPLETED =     2

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

YOU ARE SUPPOSED TO PUT A BLANK CARD BETWEEN JOBS.
I HAVE NOT FOUND IT.  I SHALL GO AHEAD AND WRITE THE
CARD I HAVE JUST READ AS THE JOB DESCRIPTION FOR THE NEXT JOB.


 CURRENT TIME = 22:51:41.62
HEATINGS, A MULTI-DIMENSIONAL HEAT CONDUCTION CODE WITH TEMPERATURE-DEPENDENT THERMAL PROPERTIES,
NON-LINEAR AND SURFACE-TO-SURFACE BOUNDARY CONDITIONS AND CHANGE-OF-PHASE CAPABILITIES.
THIS VERSION OF THE CODE IS DESCRIBED IN ORNL/TM/CSD-15.
THE TRANSIENT SOLUTION CAN BE CALCULATED BY AN IMPLICIT TECHNIQUE (CRANK-NICOLSON OR
BACKWARDS EULER) FOR PROBLEMS WITH MATERIALS WHICH ARE NOT ALLOWED TO UNDERGO A PHASE CHANGE.
THE ONE-DIMENSIONAL R SPHERICAL MODEL WAS ADDED NOV. 75. THIS MODEL MAY BE ACCESSED
BY SPECIFYING NGEOM = 10 IN THE INPUT DATA.
HEATINGS WAS WRITTEN BY
```

```
CURRENT TIME = 14:35:22.61                    DATE :  9/16/1992
HEATING5, A MULTI-DIMENSIONAL HEAT CONDUCTION CODE WITH TEMPERATURE-DEPENDENT THERMAL PROPERTIES,
NON-LINEAR AND SURFACE-TO-SURFACE BOUNDARY CONDITIONS AND CHANGE-OF-PHASE CAPABILITIES.
THIS VERSION OF THE CODE IS DESCRIBED IN ORNL/TM/CSD-15.
THE TRANSIENT SOLUTION CAN BE CALCULATED BY AN IMPLICIT TECHNIQUE (CRANK-NICOLSON OR
BACKWARDS EULER) FOR PROBLEMS WITH MATERIALS WHICH ARE NOT ALLOWED TO UNDERGO A PHASE CHANGE.
THE ONE-DIMENSIONAL R SPHERICAL MODEL WAS ADDED NOV. 75. THIS MODEL MAY BE ACCESSED
BY SPECIFYING NGEOM = 10 IN THE INPUT DATA.
HEATING5 WAS WRITTEN BY

     W.D. TURNER
     D.C. ELROD
     I.I. SIMAN-TOV
     COMPUTER SCIENCES DIVISION
     UNION CARBIDE CORPORATION, NUCLEAR DIVISION
            OAK RIDGE, TENNESSEE 37830

THIS VERSION OF HEATING CAN HANDLE A MAXIMUM OF    400 LATTICE POINTS.

INPUT RETURN

  JOB DESCRIPTION-- ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half
  GEOMETRY TYPE NUMBER     2 (OR RT  )
  NUMBER OF REGIONS     8
  NUMBER OF MATERIALS     4
  NUMBER OF HEAT GENERATION FUNCTIONS     1
  NUMBER OF INITIAL TEMPERATURE FUNCTIONS     1
  NUMBER OF DIFFERENT KINDS OF BOUNDARIES     1
  THIS PROBLEM INVOLVES TEMPERATURE-DEPENDENT PROPERTIES.
  NUMBER OF POINTS IN GROSS X OR R LATTICE     9
  NUMBER OF POINTS IN GROSS Y OR THETA LATTICE     2
  NUMBER OF POINTS IN GROSS Z LATTICE     0
  NUMBER OF ANALYTIC FUNCTIONS     1
  NUMBER OF TABULAR FUNCTIONS     8
  NUMBER OF TRANSIENT PRINTOUTS SPECIFIED     8
  TEMPERATURES OF SELECTED NODES WILL BE MONITORED EVERY  1000 ITERATIONS OR TIME STEPS.
  PROBLEM TYPE NUMBER     3
  STEADY STATE CONVERGENCE CRITERION  1.00000000-05
  MAXIMUM NUMBER OF STEADY-STATE ITERATIONS   1000
  NUMBER OF ITERATIONS BETWEEN TEMPERATURE DEPENDENT
  PARAMETER EVALUATIONS FOR STEADY STATE CALCULATIONS     0
  INITIAL OVERRELAXATION FACTOR (BETA) FOR STEADY STATE CALCULATIONS  1.90000000
  TIME INCREMENT  1.00000000-03
  LEVY'S EXPLICIT METHOD WILL BE USED WITH A TIME STEP    1 TIMES
  LARGER THAN THAT USED IN THE STANDARD TRANSIENT TECHNIQUE.
  INITIAL TIME  0.00000000-01
  FINAL TIME  2.00000000+00
```

PAGE 2

SUMMARY OF REGION DATA

NUMBERS AND FCN NUMBER				****** DIMENSIONS ******						-------- BOUNDARY NUMBERS --------					
REG. NO.	MATL NO.	INIT TEMP	HEAT GEN.	LEFT-X-OR INNER-R	RIGHT-X-OR OUTER-R	LOWER-Y-OR LEFT-THETA	UPPER-Y-OR RIGHT-THETA	REAR-Z	FRONT-Z	LF-X IN-R	RT-X OT-R	LO-Y LF-O	UP-Y RT-O	RR-Z	FT-Z
1	1	1	0	0.0000	0.0032	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
2	2	1	1	0.0032	0.0114	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
3	1	1	0	0.0114	0.0118	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
4	2	1	1	0.0118	0.0168	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
5	1	1	0	0.0168	0.0170	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
6	3	1	0	0.0170	0.0180	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
7	1	1	0	0.0180	0.0181	0.0000	3.1416	0.0000	0.0000	0	0	0	0	0	0
8	4	1	0	0.0181	0.0186	0.0000	3.1416	0.0000	0.0000	0	1	0	0	0	0

********** SUMMARY OF MATERIAL DATA **********

MATERIAL NUMBER	MATERIAL NAME	------------ THERMAL PARAMETERS ------------		
		-- TEMPERATURE-DEPENDENT FUNCTION NUMBERS --		
		CONDUCTIVITY	DENSITY	SPECIFIC HEAT
1	HEVOID	0.0000000-01	0.0000000-01	5.1920000+03
		-6	-7	0
2	FUEL	2.4000000+01	3.5500000+03	0.0000000-01
		0	0	-1
3	HECUP	0.0000000-01	8.5700000+03	2.7000000+02
		-5	0	0
4	SS	0.0000000-01	7.9500000+03	5.0200000+02
		-2	0	0

********** SUMMARY OF INITIAL TEMPERATURE DATA **********

NUMBER	INITIAL TEMPERATURE	POSITION-DEPENDENT FUNCTION NUMBERS X OR R	Y OR TH	Z
1	2.000000+01	0	0	0

***************** SUMMARY OF HEAT GENERATION RATE DATA *****************

NUMBER	POWER DENSITY	TIME-, TEMPERATURE-, AND POSITION-DEPENDENT NUMBERS TIME	TEMPERATURE	X OR R	Y OR TH	Z
1	1.000000+00	-3	0	-4	0	0

PAGE 6

**********SUMMARY OF BOUNDARY DATA**********

-------GENERAL------			--TEMPERATURE-- INFORMATION		------HEAT TRANSFER COEFFICIENTS------ RELATED FUNCTION NUMBERS				
NO.	TYPE	FCT FLAG	TEMPERATURE & TIME FCT	ASSOC. FCTS	FORCED CONV.	RADIATION	NATURAL CONV	EXPONENT	FLUX
1	1	2	1.000000+00		1.000000+00	0.000000-01	0.000000-01	0.000000-01	0.000000-01
			-8	TIME	0	0	0	0	0
				TEMP	1	0	0	0	0

GROSS LATTICES AND NUMBERS OF INCREMENTS

R OR X

0.000000	0.003180	0.011430	0.011810	0.016760	0.016967	0.017963	0.018080
0.018610							
2	4	1	4	1	1	1	1

THETA OR Y

0.000000	3.141593
1	

LISTING OF ANALYTIC FUNCTIONS

F(V)= A(1) + A(2)*V + A(3)*V**2 + A(4)*COS(A(5)*V) + A(6)*EXP(A(7)*V) + A(8)*SIN(A(9)*V) + A(10)*LOG(A(11)*V)

NO.	A(1)	A(2)	A(3)	A(4)	A(5)	A(6)	A(7)	A(8)	A(9)	A(10)	A(11)
1	0.0000-01	1.0000+00	2.7980-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01

LISTING OF TABULAR FUNCTIONS

TABLE NUMBER 1 NUMBER OF PAIRS - 25

ARGUMENT	VALUE
1.000000000+01	8.368000000+02
5.000000000+01	9.204800000+02
1.000000000+02	9.623200000+02
2.000000000+02	1.046000000+03
3.000000000+02	1.143626600+03
4.000000000+02	1.202900000+03
5.000000000+02	1.263568000+03
6.000000000+02	1.310986600+03
7.000000000+02	1.350834200+03
8.000000000+02	1.385950000+03
9.000000000+02	1.417911100+03
1.000000000+03	1.447664000+03
1.100000000+03	1.472007200+03
1.200000000+03	1.495780000+03
1.300000000+03	1.519113800+03
1.400000000+03	1.542102800+03
1.500000000+03	1.562026600+03
1.600000000+03	1.584690000+03
1.700000000+03	1.604687000+03
1.800000000+03	1.624786600+03
1.900000000+03	1.644972600+03
2.000000000+03	1.631400000+03
2.100000000+03	1.681569500+03
2.200000000+03	1.700225400+03
2.310000000+03	1.720692600+03

TABLE NUMBER 2 NUMBER OF PAIRS - 4

ARGUMENT	VALUE
2.000000000+01	1.730000000+01
1.000000000+02	1.730000000+01
2.000000000+02	1.730000000+01
3.000000000+02	1.900000000+01

TABLE NUMBER 3 NUMBER OF PAIRS - 3

ARGUMENT	VALUE
0.000000000-01	1.010604600+01
1.300000000-02	6.467900000+10
2.600000000-02	1.010604600+01

TABLE NUMBER 4 NUMBER OF PAIRS - 11

ARGUMENT	VALUE
3.180000000-03	8.100000000-01
4.000000000-03	8.200000000-01
6.000000000-03	8.400000000-01
8.000000000-03	8.600000000-01
1.000000000-02	9.200000000-01
1.143000000-02	9.800000000-01
1.181000000-02	1.000000000+00
1.200000000-02	1.000000000+00
1.400000000-02	1.100000000+00
1.600000000-02	1.240000000+00

1.700000000-02	1.280000000+00

PAGE 6

TABLE NUMBER 5 NUMBER OF PAIRS - 6

ARGUMENT	VALUE
0.000000000-01	5.230000000+01
1.000000000+02	5.440000000+01
2.000000000+02	5.650000000+01
3.000000000+02	5.860000000+01
4.000000000+02	6.070000000+01
1.000000000+03	7.270000000+01

TABLE NUMBER 6 NUMBER OF PAIRS - 18

ARGUMENT	VALUE
2.000000000+01	7.200000000-02
1.000000000+02	7.200000000-02
2.000000000+02	1.150000000-01
3.000000000+02	1.510000000-01
4.000000000+02	1.840000000-01
5.000000000+02	2.180000000-01
6.000000000+02	2.500000000-01
7.000000000+02	2.780000000-01
8.000000000+02	3.040000000-01
9.000000000+02	3.300000000-01
1.000000000+03	3.540000000-01
1.200000000+03	4.050000000-04
1.400000000+03	4.550000000-04
1.600000000+03	5.020000000-04
1.800000000+03	5.430000000-04
2.000000000+03	5.790000000-01
2.500000000+03	6.570000000-01
3.000000000+03	7.450000000-01

TABLE NUMBER 7 NUMBER OF PAIRS - 3

ARGUMENT	VALUE
2.000000000+01	3.282800000-01
1.200000000+03	1.633400000-01
2.600000000+03	1.675320000-01

TABLE NUMBER 8 NUMBER OF PAIRS - 2

ARGUMENT	VALUE
0.000000000-01	2.000000000+01
1.000000000+01	2.000000000+01

TABLE OF OUTPUT TIMES

OUTPUT NO.	OUTPUT TIME	OUTPUT NO.	OUTPUT TIME	OUTPUT NO.	OUTPUT TIME	OUTPUT NO.	OUTPUT TIME
1	0.000000-01						
2	1.300000-02						
3	2.600000-02						
4	3.000000-02						
5	1.000000-01						
6	5.000000-01						
7	1.000000+00						
8	2.000000+00						

```
TEMPERATURES OF THE FOLLOWING NODES WILL BE MONITORED
EVERY 1000 ITERATIONS OR TIME STEPS.
```

PAGE 7

NUMBER	NODE
1	1

FINE LATTICE, X OR R, Y OR THETA, AND Z

2	0.001590	3	0.003180	4	0.005242	5	0.007305	6	0.009367
7	0.011430	8	0.011810	9	0.013048	10	0.014285	11	0.015523
12	0.016760	13	0.016967	14	0.017963	15	0.018080	16	0.018610

1	0.000000	2	3.141593

THIS PROBLEM CONTAINS 30 NODES.

***** TABLE 6 MUST BE EVALUATED FOR 2.000000000+01
THE VALUE OF THE FUNCTION WILL BE 7.200000000-02 FOR ALL ARGUMENTS LESS THAN 2.000000000+01

***** TABLE 2 MUST BE EVALUATED FOR 2.000000000+01
THE VALUE OF THE FUNCTION WILL BE 1.730000000+01 FOR ALL ARGUMENTS LESS THAN 2.000000000+01

***** TABLE 7 MUST BE EVALUATED FOR 2.000000000+01
THE VALUE OF THE FUNCTION WILL BE 3.282800000-01 FOR ALL ARGUMENTS LESS THAN 2.000000000+01

PAGE 9

STABILITY CRITERION FOR EACH NODE

1	3.73220-02	2	2.28990-01	3	2.65680-01	4	2.67690-01	5	2.68530-01	6	2.77210-01
7	9.37870-02	8	9.70570-02	9	9.70720-02	10	9.70830-02	11	9.71400-02	12	2.13290-02
13	2.18220-02	14	3.15810-02	15	3.24980-02	16	3.73220-02	17	2.28990-01	18	2.65680-01
19	2.67690-01	20	2.68530-01	21	2.77210-01	22	9.37870-02	23	9.70570-02	24	9.70720-02
25	9.70830-02	26	9.71400-02	27	2.13290-02	28	2.18220-02	29	3.15810-02	30	3.24980-02

THE STABILITY CRITERION IS 2.13287190-02 FOR POINT 12

THE INPUT TIME INCREMENT SATISFIES THE STABILITY CRITERION.

```
 CURRENT TIME = 14:35:24.75
HEATINGS                   ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half        IBM PC
                                                 MAP OF THE NODE NUMBERS
GROSS GRID          1               2                               3       4                               5       6
                    I               I                               I       I                               I       I
   FINE GRID        1       2       3       4       5       6       7       8       9       10      11      12      13
       DISTANCE     0.00    0.00    0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                    I---------------I-------------------------------I-------I-------------------------------I-------I--
 1   1     0.00     0I      1       2I      3       4       5       6I      7I      8       9       10      11I     12I
 2   2     3.14     0I------16------17I-----18------19------20------21I-----22I-----23------24------25------26I-----27I--


GROSS GRID          7       8       9
                    I       I       I
   FINE GRID        14      15      16
       DISTANCE     0.02    0.02    0.02
                 -----------I-------I
 1   1     0.00     13I     14I     15I
 2   2     3.14  ---28I-----29I-----30I
```

```
CURRENT TIME = 14:35:25.24
HEATINGS                    ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half          IBM PC
                         STEADY STATE TEMPERATURE DISTRIBUTION  AFTER    0 ITERATIONS, TIME = 0.000000-01
GROSS GRID          1                   2                                       3          4                                        5         6
                    I                   I                                       I          I                                        I         I
  FINE GRID         1         2         3         4         5         6         7          8         9        10        11         12        13
     DISTANCE     0.00      0.00      0.00      0.01      0.01      0.01      0.01       0.01      0.01      0.01      0.02       0.02      0.02
                    I-------------------I---------------------------------------I----------I----------------------------------------I---------I--
 1   1    0.00    0.00     20.00     20.00     20.00     20.00     20.00     20.00      20.00     20.00     20.00     20.00      20.00     20.00
 2   2    3.14    0.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00


GROSS GRID          7         8         9
                    I         I         I
  FINE GRID        14        15        16
     DISTANCE     0.02      0.02      0.02
               --------------I---------I
 1   1    0.00   20.00     20.00     20.00
 2   2    3.14 ---20.00----20.00----20.00

                         TEMPERATURES ON NUMBERED BOUNDARIES

                       BOUNDARY NUMBER     TEMPERATURE
                              1             20.000000

   THE  MAXIMUM  TEMPERATURE  IS -  2.000000+01       (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -          1          2          3          4          5
                                            6          7          8          9         10
                                           11         12         13         14         15
                                           16         17         18         19         20
                                           21         22         23         24         25
                                           26         27         28         29         30

   THE    ·,MUM  TEMPERATURE  IS -  2.000000+01       (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -          1          2          3          4          5
                                            6          7          8          9         10
                                           11         12         13         14         15
                                           16         17         18         19         20
                                           21         22         23         24         25
                                           26         27         28         29         30
```

BEGIN THE STEADY STATE CALCULATIONS

NUMBER OF ITERATIONS	CONVERGENCE	NODE	TEMPERATURE	EXTRAPOLATION FACTOR

```
 CURRENT TIME = 14:35:25.74
HEATINGS                 ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half         IBM PC
                       STEADY STATE TEMPERATURE DISTRIBUTION  AFTER    2 ITERATIONS, TIME = 0.000000-01
GROSS GRID         1                 2                                     3        4                                   5        6
                   I                 I                                     I        I                                   I        I
  FINE GRID        1        2        3        4        5        6        7        8        9       10       11       12       13
     DISTANCE   0.00     0.00     0.00     0.01     0.01     0.01     0.01     0.01     0.01     0.01     0.02     0.02     0.02
                   I-----------------I-------------------------------------I--------I-----------------------------------I--------I--
 1  1    0.00   0.00    20.00    20.00    20.00    20.00    20.00    20.00    20.00    20.00    20.00    20.00    20.00    20.00
 2  2    3.14   0.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00


GROSS GRID         7        8        9
                   I        I        I
  FINE GRID       14       15       16
     DISTANCE   0.02     0.02     0.02
              -------------I--------I
 1  1    0.00  20.00    20.00    20.00
 2  2    3.14 ---20.00----20.00----20.00
```

TEMPERATURES ON NUMBERED BOUNDARIES

BOUNDARY NUMBER	TEMPERATURE
1	20.000000

THE MAXIMUM TEMPERATURE IS - 2.000000+01 (+-0.1)

MAX. TEMP. APPEARS AT NODES -

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25
26	27	28	29	30

THE MINIMUM TEMPERATURE IS - 2.000000+01 (+-0.1)

MIN. TEMP. APPEARS AT NODES -

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25
26	27	28	29	30

THE STEADY STATE CALCULATIONS HAVE BEEN COMPLETED.

NUMBER OF ITERATIONS COMPLETED = 2

```
CURRENT TIME = 14:35:26.34
HEATINGS                         ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half         IBM PC
                                 TRANSIENT TEMPERATURE DISTRIBUTION  AFTER    1 TIME STEPS, TIME = 1.000000-03
GROSS GRID          1               2                                         3       4                                5        6
                    I               I                                         I       I                                I        I
  FINE GRID         1       2       3       4       5       6       7       8       9       10      11      12      13
      DISTANCE      0.00    0.00    0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                    I---------------I-----------------------------------------I-------I--------------------------------I--------I--
 1  1       0.00    0.00    20.00   20.00   20.00   20.00   20.00   20.00   20.00   20.00   20.00   20.00   20.00   20.00
 2  2       3.14    0.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00----20.00


GROSS GRID          7       8       9
                    I       I       I
  FINE GRID         14      15      16
      DISTANCE      0.02    0.02    0.02
                --------------I--------I
 1  1       0.00    20.00   20.00   20.00
 2  2       3.14 ---20.00----20.00----20.00

                         TEMPERATURES ON NUMBERED BOUNDARIES

                      BOUNDARY NUMBER      TEMPERATURE
                             1              20.000000

                    THE CURRENT TIME STEP (DELTAT) = 1.000000000-03

    THE  MAXIMUM  TEMPERATURE  IS -  2.000000+01        (+-0.1)

    MAX. TEMP. APPEARS AT NODES   -          1       2       3       4       5
                                             6       7       8       9      10
                                            11      12      13      14      15
                                            16      17      18      19      20
                                            21      22      23      24      25
                                            26      27      28      29      30

    THE  MINIMUM  TEMPERATURE  IS -  2.000000+01        (+-0.1)

    MIN. TEMP. APPEARS AT NODES   -          1       2       3       4       5
                                             6       7       8       9      10
                                            11      12      13      14      15
                                            16      17      18      19      20
                                            21      22      23      24      25
                                            26      27      28      29      30
```

```
CURRENT TIME = 14:35:28.16
HEATINGS                  ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half          IBM PC
                          TRANSIENT TEMPERATURE DISTRIBUTION  AFTER   13 TIME STEPS, TIME = 1.300000-02
GROSS GRID         1               2                                    3       4                                5        6
                   I               I                                    I       I                                I        I
  FINE GRID        1       2       3        4       5       6           7       8       9       10      11      12       13
     DISTANCE    0.00    0.00    0.00     0.01    0.01    0.01        0.01    0.01    0.01    0.01    0.02    0.02     0.02
                   I---------------I------------------------------------I-------I--------------------------------I--------I--
1  1    0.00     0.00   27.62  115.82   118.35  120.70  126.09      134.79  137.31  142.99  150.45  159.87  166.53    20.15
2  2    3.14     0.00----27.62---115.82---118.35---120.70---126.09---134.79---137.31---142.99---150.45---159.87---166.53----20.15


GROSS GRID         7       8       9
                   I       I       I
  FINE GRID       14      15      16
     DISTANCE    0.02    0.02    0.02
              --------------I--------I
1  1    0.00    20.02   20.00   20.00
2  2    3.14 ---20.02----20.00----20.00

                    TEMPERATURES ON NUMBERED BOUNDARIES

                    BOUNDARY NUMBER      TEMPERATURE
                          1               20.000000

                 THE CURRENT TIME STEP (DELTAT) = 1.000000000-03

   THE  MAXIMUM  TEMPERATURE  IS -  1.665300+02       (+-0.1)

   MAX. TEMP. APPEARS AT NODES  -         11         26

   THE  MINIMUM  TEMPERATURE  IS -  2.001620+01       (+-0.1)

   MIN. TEMP. APPEARS AT NODES  -         13         14         15         28         29
                                          30
```

```
CURRENT TIME = 14:35:29.97
HEATINGS                    ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half        IBM PC
                            TRANSIENT TEMPERATURE DISTRIBUTION  AFTER   26 TIME STEPS, TIME = 2.60000D-02
GROSS GRID          1          2                             3       4                              5       6
                    I          I                             I       I                              I       I
  FINE GRID         1     2    3     4      5      6         7       8       9      10     11      12      13
     DISTANCE     0.00  0.00  0.00  0.01   0.01   0.01      0.01    0.01    0.01   0.01   0.02    0.02    0.02
                  I--------------I-----------------------------I---------I-------------------------------I---------I--
1  1     0.00     0.00  71.40  217.84  222.75  227.47  238.13  254.67  260.71  271.16  285.59  303.36  315.02  21.06
2  2     3.14     0.00----71.40---217.84---222.75---227.47---238.13---254.67---260.71---271.16---285.59---303.36---315.02----21.06


GROSS GRID          7       8       9
                    I       I       I
  FINE GRID        14      15      16
     DISTANCE     0.02    0.02    0.02
              --------------I---------I
1  1     0.00    20.26   20.00   20.00
2  2     3.14 ---20.26----20.00----20.00

                    TEMPERATURES ON NUMBERED BOUNDARIES

                    BOUNDARY NUMBER      TEMPERATURE
                          1               20.000000

              THE CURRENT TIME STEP (DELTAT) = 1.000000000-03

   THE  MAXIMUM  TEMPERATURE  IS -  3.150160+02       (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -         11        26

   THE  MINIMUM  TEMPERATURE  IS -  2.00007D+01       (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -         14        15        29        30

***** TABLE  3 MUST BE EVALUATED FOR  2.600000000-02
   THE VALUE OF THE FUNCTION WILL BE  1.010604600+01 FOR ALL ARGUMENTS GREATER THAN  2.600000000-02
```

```
                                        PAGE    17


CURRENT TIME = 14:35:30.85
HEATINGS                     ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half         IBM PC
                             TRANSIENT TEMPERATURE DISTRIBUTION  AFTER   30 TIME STEPS, TIME = 3.000000-02
GROSS GRID          1             2                               3       4                               5       6
                    I             I                               I       I                               I       I
  FINE GRID         1      2      3      4      5      6      7      8      9      10     11     12     13
     DISTANCE     0.00   0.00   0.00   0.01   0.01   0.01   0.01   0.01   0.01   0.01   0.02   0.02   0.02
                  I-------------I-----------------------------I-------I-------------------------------I-------I--
 1  1     0.00    0.00  87.86  217.90 222.76 227.52 238.18 254.49 261.05 271.25 285.66 303.28 314.44  21.39
 2  2     3.14    0.00----87.86---217.90---222.76---227.52---238.18---254.49---261.05---271.25---285.66---303.28---314.44----21.39


GROSS GRID          7      8      9
                    I      I      I
  FINE GRID        14     15     16
     DISTANCE     0.02   0.02   0.02
               -------------I-------I
 1  1     0.00    20.42  20.00  20.00
 2  2     3.14 ---20.42----20.00----20.00

                       TEMPERATURES ON NUMBERED BOUNDARIES

                    BOUNDARY NUMBER      TEMPERATURE
                          1               20.000000

                  THE CURRENT TIME STEP (DELTAT) = 1.000000000-03

   THE  MAXIMUM  TEMPERATURE  IS -  3.144390+02      (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -        11         26

   THE  MINIMUM  TEMPERATURE  IS -  2.000130+01      (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -        14         15         29         30
```

CURRENT TIME = 14:33:39.25

HEATINGS ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half IBM PC

TRANSIENT TEMPERATURE DISTRIBUTION AFTER 100 TIME STEPS, TIME = 1.00000D-01

GROSS GRID			1		2				3	4				5	6
			I		I				I	I				I	I
FINE GRID			1	2	3	4	5	6	7	8	9	10	11	12	13
DISTANCE			0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
1	1	0.00	0.00	209.32	218.92	223.01	228.33	238.86	251.75	265.83	273.07	286.60	301.28	306.36	25.60
2	2	3.14	0.00	209.32	218.92	223.01	228.33	238.86	251.75	265.83	273.07	286.60	301.28	306.36	[illegible].60

GROSS GRID			7	8	9
			I	I	I
FINE GRID			14	15	16
DISTANCE			0.02	0.02	0.02
1	1	0.00	24.31	20.06	20.03
2	2	3.14	24.31	20.06	20.03

TEMPERATURES ON NUMBERED BOUNDARIES

BOUNDARY NUMBER	TEMPERATURE
1	20.000000

THE CURRENT TIME STEP (DELTAT) = 1.000000000-03

THE MAXIMUM TEMPERATURE IS - 3.063570+02 (+-0.1)

MAX. TEMP. APPEARS AT NODES - 11 26

THE MINIMUM TEMPERATURE IS - 2.006200+01 (+-0.1)

MIN. TEMP. APPEARS AT NODES - 14 15 29 30

```
CURRENT TIME = 14:36:26.38
HEATINGS                          ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half          IBM PC
                                  TRANSIENT TEMPERATURE DISTRIBUTION  AFTER  500 TIME STEPS, TIME = 5.00000D-01
GROSS GRID          1                 2                                         3         4                                           5         6
                    I                 I                                         I         I                                           I         I
  FINE GRID         1        2        3        4        5        6        7        8        9        10       11       12       13
     DISTANCE     0.00     0.00     0.00     0.01     0.01     0.01     0.01     0.01     0.01     0.01     0.02     0.02     0.02
                  I-----------------I---------------------------------I---------I-----------------------------------I---------I--
1   1     0.00    0.00   222.91   223.12   225.70   231.55   239.18   244.06   278.61   281.25   286.11   289.16   286.51    45.00
2   2     3.14    0.00---222.91---223.12---225.70---231.55---239.18---244.06---278.61---281.25---286.11---289.16---286.51----45.00


GROSS GRID          7        8        9
                    I        I        I
  FINE GRID        14       15       16
     DISTANCE     0.02     0.02     0.02
              --------------I---------I
1   1     0.00   43.79    21.70    21.50
2   2     3.14 ---43.79----21.70----21.50

                              TEMPERATURES ON NUMBERED BOUNDARIES

                           BOUNDARY NUMBER      TEMPERATURE
                                 1               20.000000

                        THE CURRENT TIME STEP (DELTAT) = 1.000000000D-03

    THE  MAXIMUM  TEMPERATURE  IS -  2.891580+02       (+-0.1)    *

    MAX. TEMP. APPEARS AT NODES   -          10         25

    THE  MINIMUM  TEMPERATURE  IS -  2.150100+01       (+-0.1)

    MIN. TEMP. APPEARS AT NODES   -          15         30

                                                  TABLE FOR SPECIAL MONITORING OF TEMPERATURES
NUMBER OF      TIME      ======================================== NODE NUMBERS AND TEMPERATURES ========================================
TIME STEPS
  1000      1.00000+00     1 2.268030+02
```

```
 CURRENT TIME = 14:37:25.26
HEATINGS                       ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half          IBM PC
                              TRANSIENT TEMPERATURE DISTRIBUTION  AFTER 1000 TIME STEPS, TIME = 1.000000D+00
GROSS GRID          1                 2                                      3        4                                    5        6
                    I                 I                                      I        I                                    I        I
   FINE GRID        1        2        3        4        5        6           7        8        9        10       11        12       13
      DISTANCE    0.00     0.00     0.00     0.01     0.01     0.01        0.01     0.01     0.01     0.01     0.02      0.02     0.02
                    I-----------------I--------------------------------------I--------I------------------------------------I--------I--
 1   1    0.00    0.00   226.80   226.96   228.94   233.37   238.15      240.93   281.96   282.68   282.85   281.36    277.26    64.04
 2   2    3.14    0.00---226.80---226.96---228.94---233.37---238.15---240.93---281.96---282.68---282.85---281.36---277.26----64.04


GROSS GRID          7        8        9
                    I        I        I
   FINE GRID        14       15       16
      DISTANCE    0.02     0.02     0.02
              ---------------I--------I
 1   1    0.00   62.87    25.95    25.59
 2   2    3.14 ---62.87----25.95----25.59
```

TEMPERATURES ON NUMBERED BOUNDARIES

BOUNDARY NUMBER	TEMPERATURE
1	20.000000

THE CURRENT TIME STEP (DELTAT) = 1.000000000-03

THE MAXIMUM TEMPERATURE IS - 2.828540+02 (+-0.1)

MAX. TEMP. APPEARS AT NODES - 9 24

THE MINIMUM TEMPERATURE IS - 2.559260+01 (+-0.1)

MIN. TEMP. APPEARS AT NODES - 15 30

```
                                                PAGE  21


CURRENT TIME = 14:39:22.63
HEATINGS                          ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half         IBM PC
                                  TRANSIENT TEMPERATURE DISTRIBUTION  AFTER 2000 TIME STEPS, TIME = 2.00000D+00
GROSS GRID          1                2                                        3        4                                        5        6
                    I                I                                        I        I                                        I        I
  FINE GRID         1       2        3        4        5        6             7        8        9        10       11       12       13
      DISTANCE   0.00    0.00     0.00     0.01     0.01     0.01          0.01     0.01     0.01     0.01     0.02     0.02     0.02
                    I----------------I----------------------------------------I--------I----------------------------------------I--------I--
 1  1     0.00   0.00  231.74   231.82   232.81   234.96   237.26        238.93   277.87   277.82   276.33   273.46   269.29    92.32
 2  2     3.14   0.00---231.74---231.82---232.81---234.96---237.26---238.93---277.87---277.82---276.33---273.46---269.29----92.32


GROSS GRID          7        8        9
                    I        I        I
  FINE GRID        14       15       16
      DISTANCE   0.02     0.02     0.02
              --------------I--------I
 1  1     0.00  91.20    38.06    37.49
 2  2     3.14 ---91.20----38.06----37.49

                          TEMPERATURES ON NUMBERED BOUNDARIES

                           BOUNDARY NUMBER      TEMPERATURE
                                  1              20.000000

                       THE CURRENT TIME STEP (DELTAT) = 1.000000000D-03

   THE  MAXIMUM  TEMPERATURE  IS -  2.778660+02        (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -           7          8         22         23

   THE  MINIMUM  TEMPERATURE  IS -  3.749490+01        (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -          15         30

      THE TRANSIENT CALCULATIONS HAVE BEEN COMPLETED.

      FINAL TIME IS     2.00000D+00

      NUMBER OF TIME STEPS COMPLETED =  2000
```

BEGIN THE STEADY STATE CALCULATIONS

NUMBER OF ITERATIONS	CONVERGENCE	NODE	TEMPERATURE	EXTRAPOLATION FACTOR
3	1.21343E-01	30	4.96150E+01	-5.62747E+00
8	5.43990E-02	29	7.25892E+01	3.96383E+00
13	-3.39722E-02	22	1.75415E+02	-2.41683E+02
18	-3.60894E-02	18	2.11762E+02	-7.47103E+01
23	-3.43653E-02	16	1.85117E+02	5.43442E+01
28	-2.66383E-02	1	1.63140E+02	1.14671E+01
33	-2.12732E-02	7	1.18485E+02	1.68687E+01
38	-1.99725E-02	22	1.05925E+02	2.42766E+01
			BETA REDUCED TO	1.800
43	-1.44393E-02	1	1.23010E+02	1.79680E+01
48	-1.08847E-02	1	1.16987E+02	4.93540E+00
53	-9.60156E-03	16	1.10965E+02	6.91876E+00
58	-9.40249E-03	16	1.05867E+02	-1.83456E+02
			BETA REDUCED TO	1.700
63	-7.52996E-03	1	1.02173E+02	3.47737E+01
68	-6.18464E-03	1	9.92093E+01	1.29906E+01
73	-5.81209E-03	2	9.60107E+01	2.45571E+01
78	-5.71397E-03	1	9.36050E+01	1.44105E+02
			BETA REDUCED TO	1.600
83	-4.69474E-03	1	9.12889E+01	4.26804E+01
88	-4.06617E-03	1	8.95008E+01	3.70082E+01
93	-3.92724E-03	2	8.75270E+01	7.03866E+01
98	-3.87175E-03	1	8.60507E+01	1.46181E+02
			BETA REDUCED TO	1.500
103	-3.22790E-03	1	8.45943E+01	6.55756E+01
108	-2.89272E-03	1	8.33970E+01	1.42101E+02
113	-2.83520E-03	1	8.22159E+01	1.50125E+02
118	-2.80210E-03	1	8.10649E+01	1.91684E+02
			EXTRAPOLATION	
123	-3.28435E-03	14	3.19117E+01	1.83604E+01
128	-2.51468E-03	14	3.14681E+01	1.88351E+01
133	-2.03941E-03	14	3.11218E+01	2.47854E+01
138	-1.73914E-03	14	3.08351E+01	3.25096E+01
			EXTRAPOLATION	
143	-1.20542E-03	25	3.46943E+01	3.22742E+00
148	-1.18613E-03	22	3.46467E+01	2.07081E+02
153	-1.16618E-03	22	3.44438E+01	2.03951E+02
158	-1.14394E-03	22	3.42457E+01	1.94632E+02
			EXTRAPOLATION	
163	-1.94107E-03	16	2.96212E+01	-2.38419E+00
168	-1.75593E-03	16	2.93512E+01	4.21791E+01
173	-1.60500E-03	16	2.91077E+01	5.09271E+01
178	-1.47100E-03	16	2.88867E+01	5.33581E+01
			EXTRAPOLATION	
183	-8.93310E-04	9	2.63350E+01	1.83098E+00
188	-8.58797E-04	8	2.62435E+01	9.93293E+01
193	-8.15208E-04	7	2.61509E+01	8.48403E+01
198	-7.69896E-04	7	2.60480E+01	7.99149E+01
			EXTRAPOLATION	
203	-1.24030E-03	14	2.34892E+01	-2.45588E+00
208	-9.50890E-04	16	2.57174E+01	4.56206E+01
213	-8.70114E-04	16	2.56016E+01	5.38411E+01
218	-7.99608E-04	16	2.54960E+01	5.74205E+01
			EXTRAPOLATION	
223	-6.12519E-04	8	2.41553E+01	4.40412E+00

228	-5.84991E-04	8	2.40834E+01	9.05399E+01

233	-5.53289E-04	7	2.40258E+01	8.19855E+01
238	-5.21403E-04	7	2.39617E+01	7.95716E+01
			EXTRAPOLATION	
243	-7.55059E-04	16	2.23195E+01	-2.93107E+00
248	-6.42464E-04	16	2.37508E+01	5.21359E+01
253	-5.87723E-04	16	2.36786E+01	5.49831E+01
258	-5.40725E-04	1	2.36170E+01	5.99088E+01
			EXTRAPOLATION	
263	-4.19386E-04	8	2.27564E+01	4.70834E+00
268	-3.98354E-04	7	2.27169E+01	8.63179E+01
273	-3.75862E-04	7	2.26732E+01	8.04556E+01
278	-3.53773E-04	7	2.26322E+01	7.96942E+01
			EXTRAPOLATION	
283	-4.78611E-04	16	2.25438E+01	-3.38873E+00
288	-4.36144E-04	16	2.24928E+01	5.28588E+01
293	-3.99093E-04	16	2.24464E+01	5.57761E+01
298	-3.67539E-04	1	2.24067E+01	6.03814E+01
			EXTRAPOLATION	
303	-2.87226E-04	8	2.18443E+01	4.92564E+00
308	-2.71793E-04	7	2.18184E+01	8.43490E+01
313	-2.55862E-04	7	2.17898E+01	7.90756E+01
318	-2.40570E-04	7	2.17629E+01	7.95052E+01
			EXTRAPOLATION	
323	-3.24904E-04	16	2.17038E+01	-3.39908E+00
328	-2.96070E-04	16	2.16705E+01	5.33055E+01
333	-2.71078E-04	1	2.16420E+01	5.72084E+01
338	-2.49656E-04	1	2.16141E+01	6.08443E+01
			EXTRAPOLATION	
343	-1.96793E-04	8	2.12415E+01	5.18958E+00
348	-1.85650E-04	7	2.12242E+01	8.10513E+01
353	-1.74429E-04	7	2.12053E+01	7.77541E+01
358	-1.63842E-04	7	2.11874E+01	7.90863E+01
			EXTRAPOLATION	
363	-2.20511E-04	16	2.11480E+01	-3.42394E+00
368	-2.00928E-04	16	2.11259E+01	5.36107E+01
373	-1.84023E-04	1	2.11070E+01	5.74384E+01
378	-1.69495E-04	1	2.10886E+01	6.12941E+01
			EXTRAPOLATION	
383	-1.34876E-04	8	2.08393E+01	5.50574E+00
388	-1.26910E-04	7	2.08277E+01	7.83218E+01
393	-1.19035E-04	7	2.08150E+01	7.64903E+01
398	-1.11706E-04	7	2.08031E+01	7.85308E+01
			EXTRAPOLATION	
403	-1.49638E-04	16	2.07768E+01	-3.45958E+00
408	-1.36344E-04	16	2.07621E+01	5.38443E+01
413	-1.24883E-04	1	2.07494E+01	5.76933E+01
418	-1.15049E-04	1	2.07371E+01	6.17303E+01
			EXTRAPOLATION	
423	-9.24706E-05	7	2.05705E+01	5.87737E+00
428	-8.68078E-05	7	2.05614E+01	7.59897E+01
433	-8.12954E-05	7	2.05528E+01	7.52890E+01
438	-7.62234E-05	7	2.05448E+01	7.78997E+01
			EXTRAPOLATION	
443	-1.01545E-04	16	2.05272E+01	-3.50341E+00
448	-9.25237E-05	16	2.05174E+01	5.40426E+01
453	-8.47441E-05	1	2.05089E+01	5.79607E+01
458	-7.80937E-05	1	2.05006E+01	6.21552E+01
			EXTRAPOLATION	
463	-6.34366E-05	7	2.03879E+01	6.32316E+00

468	-5.94082E-05	7	2.03817E+01	7.39559E+01

473	-5.55570E-05	7	2.03758E+01	7.41523E+01
478	-5.20472E-05	7	2.03704E+01	7.72307E+01
			EXTRAPOLATION	
483	-6.89169E-05	16	2.03587E+01	-3.55374E+00
488	-6.27962E-05	16	2.03521E+01	5.42247E+01
493	-5.75209E-05	16	2.03460E+01	5.77822E+01
498	-5.30179E-05	1	2.03408E+01	6.25719E+01
			EXTRAPOLATION	
503	-4.35288E-05	7	2.02642E+01	6.83795E+00
508	-4.06758E-05	7	2.02600E+01	7.21567E+01
513	-3.79890E-05	7	2.02560E+01	7.30794E+01
518	-3.55605E-05	7	2.02523E+01	7.65466E+01
			EXTRAPOLATION	
[illegible]	-4.67831E-05	16	2.02446E+01	-3.60954E+00
528	-4.26339E-05	16	2.02401E+01	5.44008E+01
533	-3.90623E-05	16	2.02360E+01	5.80771E+01
538	-3.60055E-05	16	2.02322E+01	6.26487E+01
			EXTRAPOLATION	
543	-2.98759E-05	7	2.01803E+01	7.43547E+00
548	-2.78621E-05	7	2.01774E+01	7.05480E+01
553	-2.59898E-05	7	2.01747E+01	7.20673E+01
558	-2.43095E-05	7	2.01722E+01	7.58605E+01
			EXTRAPOLATION	
563	-3.17664E-05	16	2.01670E+01	-3.67026E+00
568	-2.89531E-05	16	2.01640E+01	5.45765E+01
[illegible]	-2.65357E-05	16	2.01612E+01	5.83651E+01
578	-2.44690E-05	16	2.01587E+01	6.30394E+01
			EXTRAPOLATION	
583	-2.04448E-05	7	2.01232E+01	7.88578E+00
588	-1.90378E-05	7	2.01213E+01	6.94177E+01
593	-1.77437E-05	7	2.01194E+01	7.14465E+01
598	-1.65895E-05	7	2.01177E+01	7.55426E+01
			EXTRAPOLATION	
603	-2.15719E-05	16	2.01143E+01	-3.71745E+00
608	-1.96649E-05	16	2.01122E+01	5.47553E+01
613	-1.80289E-05	16	2.01104E+01	5.86498E+01
618	-1.66315E-05	16	2.01086E+01	6.34219E+01
			EXTRAPOLATION	
623	-1.40312E-05	7	2.00844E+01	8.59385E+00
628	-1.30438E-05	7	2.00830E+01	6.81307E+01
633	-1.21444E-05	7	2.00818E+01	7.05772E+01
638	-1.13466E-05	7	2.00806E+01	7.49097E+01
			EXTRAPOLATION	
643	-1.46533E-05	16	2.00784E+01	-3.78443E+00
648	-1.33606E-05	16	2.00770E+01	5.49394E+01
653	-1.22532E-05	16	2.00757E+01	5.89347E+01
658	-1.13081E-05	16	2.00745E+01	6.38006E+01
			EXTRAPOLATION	
643	-9.63158E-06	7	2.00579E+01	9.41997E+00

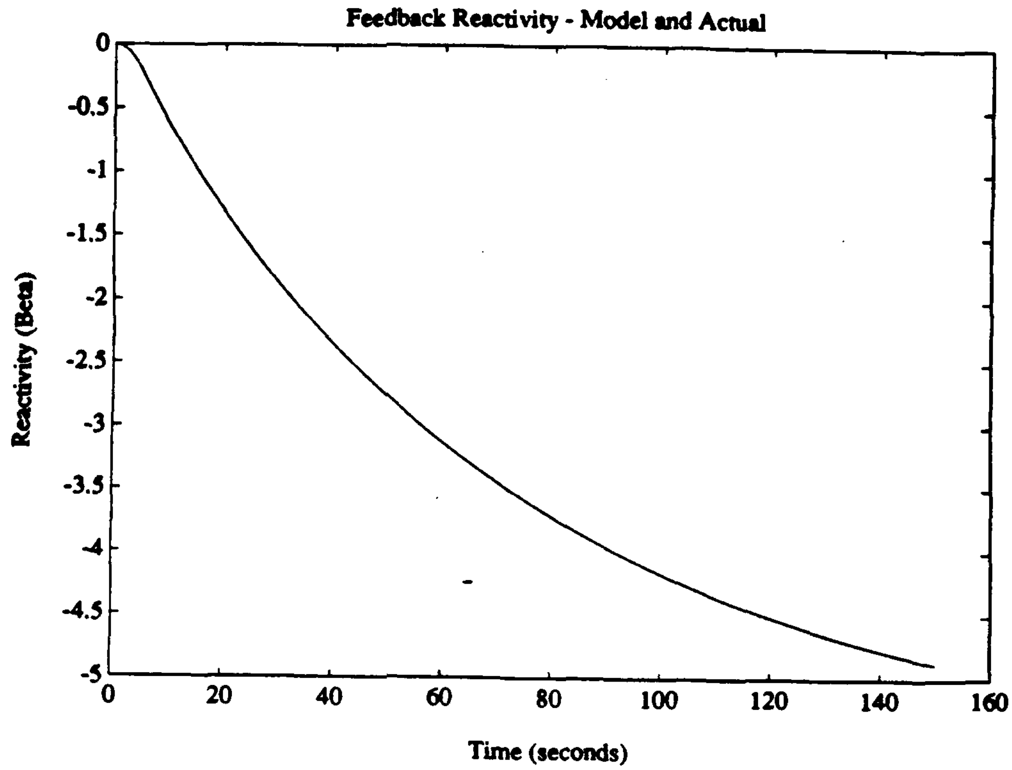
```
                                                    PAGE   25


CURRENT TIME = 14:40:16.40
HEATINGS                      ACRR HEAT DEPOSITION TRANSIENT #1 - 6400 MW pulse - 13 msec width @ half         IBM PC
                           STEADY STATE TEMPERATURE DISTRIBUTION  AFTER  663 ITERATIONS, TIME = 2.00000D+00
GROSS GRID          1              2                                      3       4                                5       6
                    I              I                                      I       I                                I       I
  FINE GRID         1       2      3       4       5       6       7      8       9      10      11      12      13
     DISTANCE     0.00    0.00   0.00    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.02    0.02    0.02
                    I--------------I--------------------------------------I-------I--------------------------------I-------I--
 1  1     0.00    0.00   20.06   20.06   20.06   20.06   20.06   20.06   20.06   20.06   20.06   20.06   20.06   20.06
 2  2     3.14    0.00----20.06----20.06----20.06----20.06----20.06----20.06----20.06----20.06----20.06----20.06----20.06----20.06



GROSS GRID          7       8       9
                    I       I       I
  FINE GRID        14      15      16
     DISTANCE     0.02    0.02    0.02
             -------------I--------I
 1  1     0.00   20.04   20.04   20.04
 2  2     3.14 ---20.04----20.04----20.04

                          TEMPERATURES ON NUMBERED BOUNDARIES

                        BOUNDARY NUMBER     TEMPERATURE
                               1             20.000000

   THE  MAXIMUM  TEMPERATURE  IS -  2.00591D+01        (+-0.1)

   MAX. TEMP. APPEARS AT NODES   -         1        2        3        4        5
                                           6        7        8        9       10
                                          11       12       13       14       15
                                          16       17       18       19       20
                                          21       22       23       24       25
                                          26       27       28       29       30

   THE  MINIMUM  TEMPERATURE  IS -  2.00591D+01        (+-0.1)

   MIN. TEMP. APPEARS AT NODES   -         1        2        3        4        5
                                           6        7        8        9       10
                                          11       12       13       14       15
                                          16       17       18       19       20
                                          21       22       23       24       25
                                          26       27       28       29       30

        THE STEADY STATE CALCULATIONS HAVE BEEN COMPLETED.

        NUMBER OF ITERATIONS COMPLETED =   663

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

YOU ARE SUPPOSED TO PUT A BLANK CARD BETWEEN JOBS.
I HAVE NOT FOUND IT.  I SHALL GO AHEAD AND WRITE THE
CARD I HAVE JUST READ AS THE JOB DESCRIPTION FOR THE NEXT JOB.
```

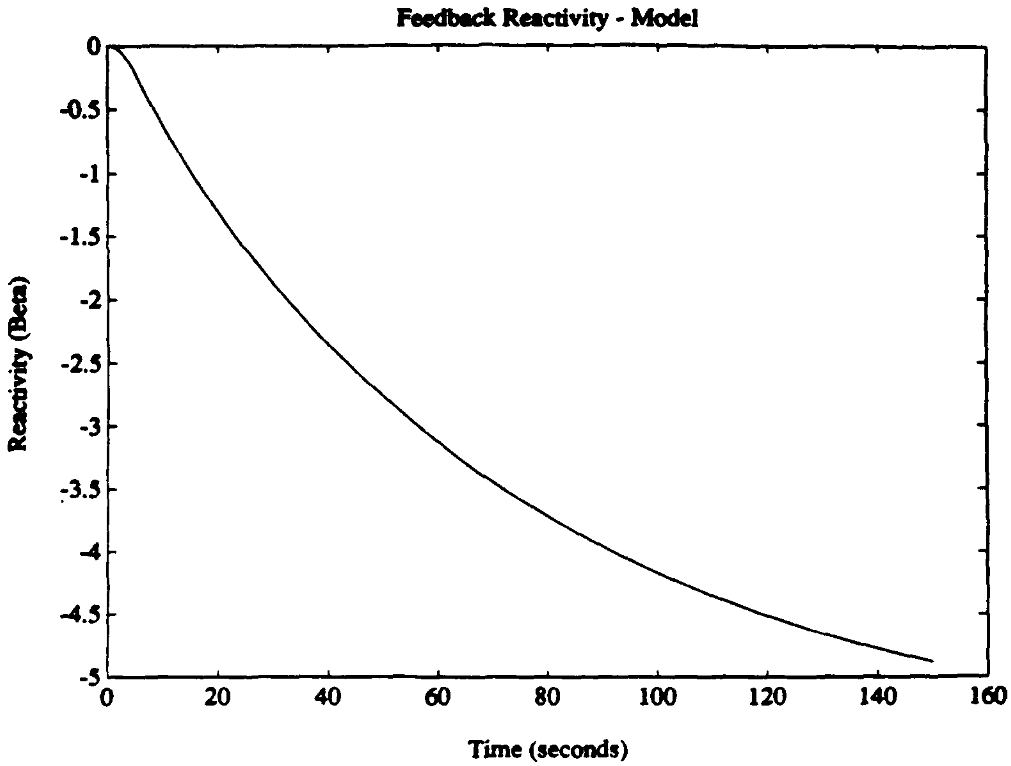
Appendix C

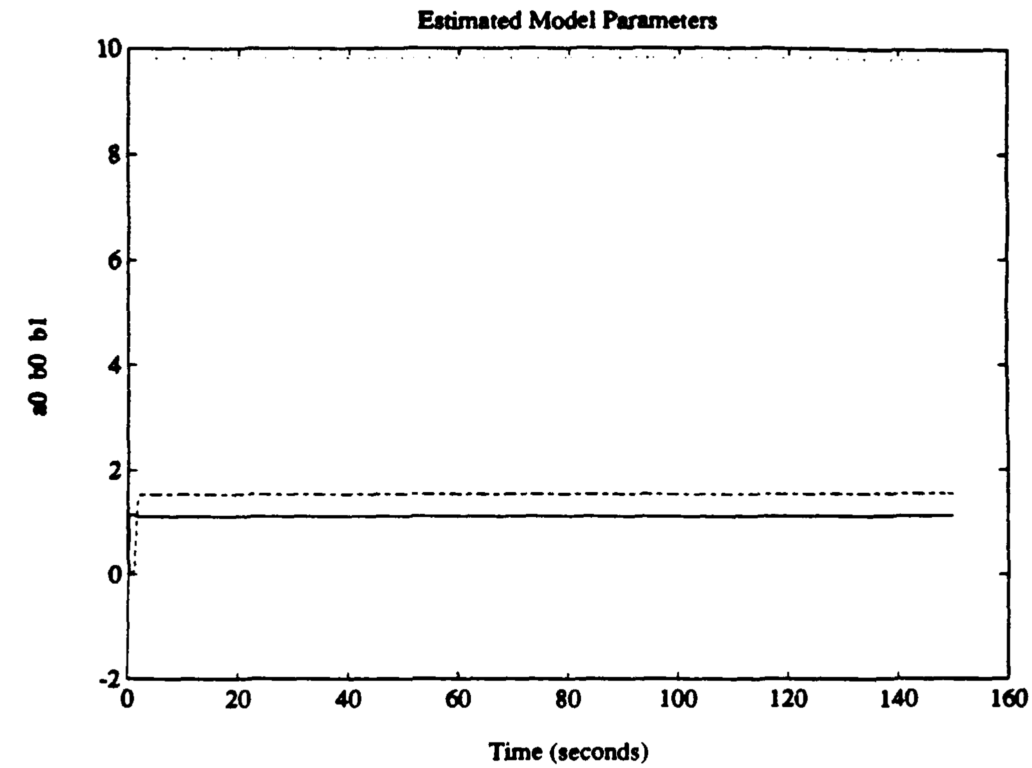
```
a0=9.8218e-4;
a1=-4.0822e-7;
a2=1.1773e-10;
b0=1.113e-1;
b1=1.5402e-4;
b2=-4.0805e-8;
c0=78.381;
c1=0.3393;
c2=-8.9181e-5;
d0=4189.8;
d1=-0.61063;
d2=0.0088811;
g0=1002.9;
g1=-0.1599;
g2=-0.0028345;
m2=-0.0151;
m1=2.9305;
m0=-49.79;
A=14.0;
df=3550;
Vf=0.09866089;
dt=0.05;
t=6.3e-7;
Vm=0.045434752;
cpm=4182;
Tm=20.0;
Tma(1)=20.0;
Tpool=20.0;
Tfint=25;
Pint=3e3;
Tfr=Tfint;
Tfm=Tfint;
Tfr1(1,1)=Tfm;
P=Pint;
reactfbint=0.0;
for i=1:3000
Tfr1(1,i+1)=Tfr-A*dt*(b0*Tfr+b1*Tfr^2+b2*Tfr^3)/(df*Vf)...
    +A*dt*Tm*(b0+b1*Tfr+b2*Tfr^2)/(df*Vf)...
    +(1-t)*dt*P*(a0+a1*Tfr+a2*Tfr^2)/(df*Vf);
heatin=dt*((A*(c0+c1*Tfr+c2*Tfr^2)*(Tfr-Tm))+(t*P))/...
((g0+g1*Tm+g2*Tm^2)*(d0+d1*Tm+d2*Tm^2)*Vm);
heatout=dt*(m0+m1*Tm+m2*Tm^2)*2*(Tm-Tpool)/((g0+g1*Tm+g2*Tm^2)*Vm);
Tma(i+1)=heatin-heatout+Tm;
Tm=Tma(i+1);
Tfr=Tfr1(1,i+1);
if i<100
P=P+3.997e4;
else
P=4e6;
end
end
for i=1:3000
  reactfb(1,i)=(Tfr1(1,i)-Tfint)*(-3.85-(730/(273.15+Tfr1(1,i))))*1e-5/0.0073;
end
```

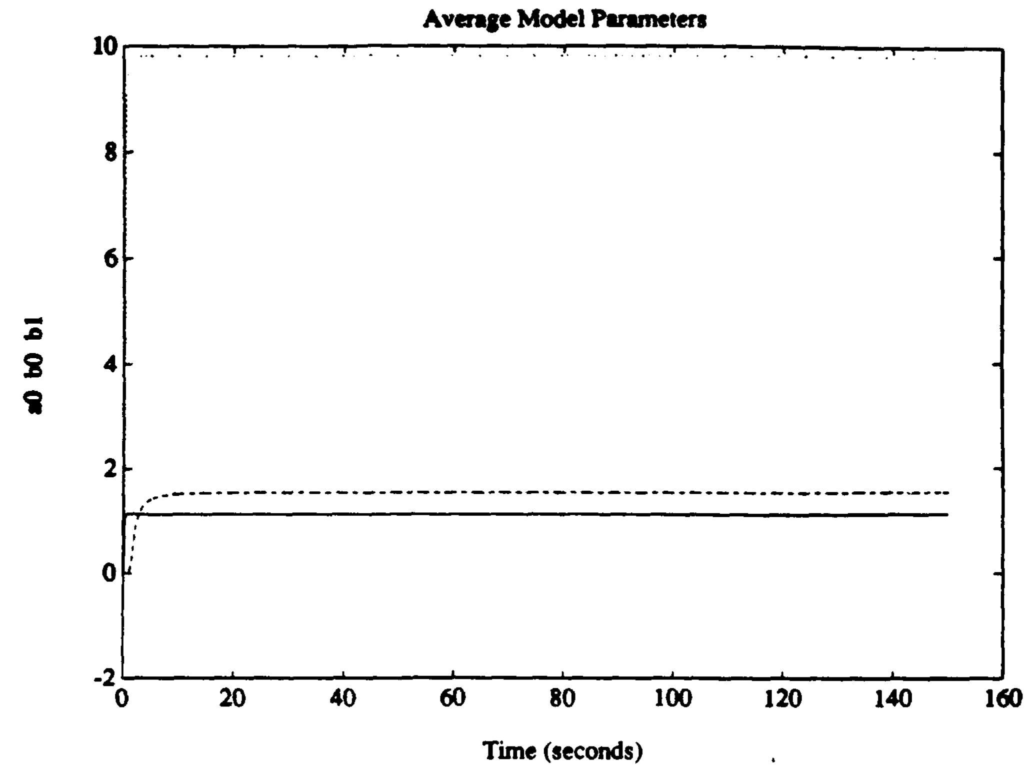
```
a0=0.0;
a1=-4.0822;
a2=1.1773e-10;;
b0=0.0;
b1=0.0;
b2=-4.0805e-8;
c0=78.381;
c1=0.3393;
c2=-8.9181e-5;
do=4189.8;
d1=-0.61063;
d2=0.0088811;
g0=1002.9;
g1=-0.1599;
g2=-0.0028345;
m0=-49.79;
m1=2.9305;
m2=-0.0151;
A=14.0;
df=3550;
Vf=0.09866089;
dt=0.05;
t=6.3e-7;
dm=998.20323;
Vm=0.045434752;
cpm=4182;
Tm=20.0;
Tm1(1)=Tm;
Tpool=20.0;
Tfint=25;
Pint=3e3;
reactfbm(1)=0.0;
Tfm=Tfint;
P=Pint;
P1(1)=Pint;
datam=[Tfm b0 b1 a0];
F1=1-A*dt*(b0*1e-1+2*b1*1e-4*Tfm+3*b2*Tfm^2)/(df*Vf)...
+A*dt*Tm*(b1*1e-4+2*b2*Tfm)/(df*Vf)+dt*(1-t)*P*(a1*1e-7+2*a2*Tfm)/(df*Vf);
F2=A*dt*1e-1*(Tm-Tfm)/(df*Vf);
F3=A*dt*1e-4*(Tm*Tfm-Tfm^2)/(df*Vf);
F4=(1-t)*P*dt*1e-4/(df*Vf);
F=[F1 F2 F3 F4;0 1 0 0;0 0 1 0;0 0 0 1];
E=inv(F*F);
j=0.0;
sumi=0.0;
b0sum=0.0;
b0ave(1)=0.0;
b1sum=0.0;
b1ave(1)=0.0;
a0sum=0.0;
a0ave(1)=0.0;
for i=1:3000
X=[Tfm b0 b1 a0]';
h=(-3.85+730*Tfm/(273.15+Tfm)^2-730/(273.15+Tfm)-730*Tfint/(273.15+Tfm)^2...
```

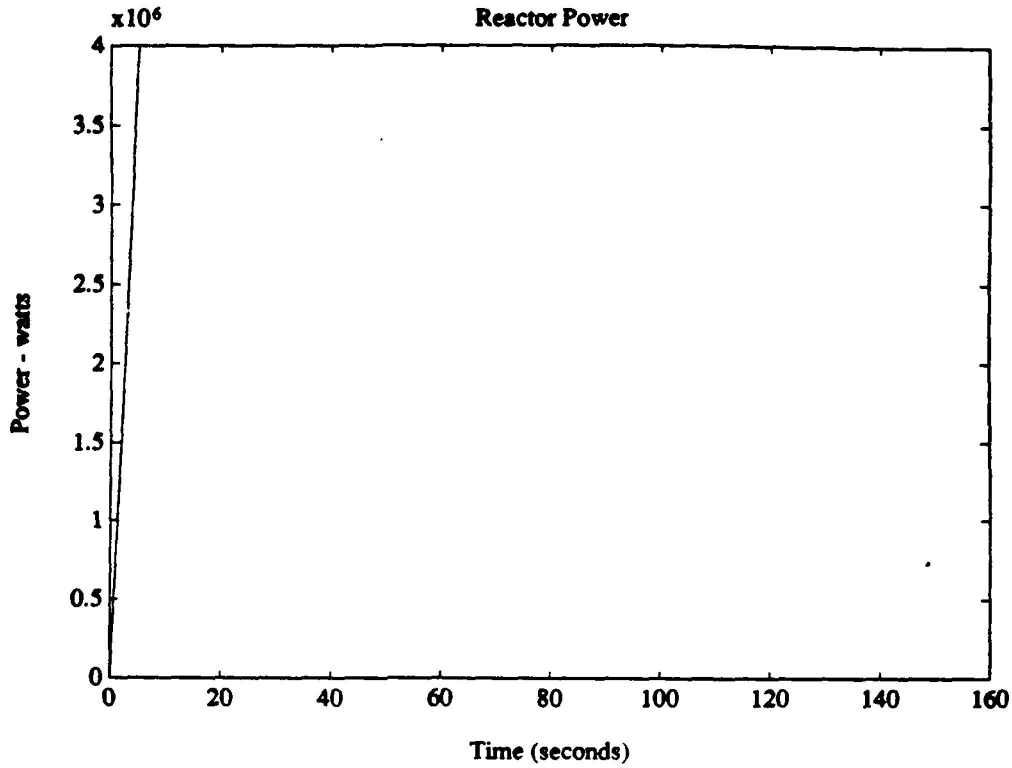
```
)*1e-5/.0073;
H=[h 0 0 0]';
O=H'*E*H+1e-15;
L=E*H*inv(O);
Y=reactfb(1,i);
xhat=X+L*(Y-(Tfm-Tfint)*(-3.85-(730/(273.15+Tfm)))*1e-5/.0073);
datam=[datam;xhat'];
Tfm=xhat(1,1);
reactfbm(i+1)=(Tfm-Tfint)*(-3.85-(730/(273.15+Tfm)))*1e-5/.0073;
Tm1(i+1)=Tm;
b0=xhat(2,1);
b1=xhat(3,1);
a0=xhat(4,1);
b0sum=b0*i+b0sum;
b1sum=b1*i+b1sum;
a0sum=a0*i+a0sum;
sumi=i+sumi;
b0ave(i+1)=b0sum/sumi;
b1ave(i+1)=b1sum/sumi;
a0ave(i+1)=a0sum/sumi;
j=j+1;
Tfm1=Tfm-A*dt*(b0*1e-1*Tfm+b1*1e-4*Tfm^2+b2*Tfm^3)/(df*Vf)...
    +A*dt*Tm*(b0*1e-1+b1*1e-4*Tfm+b2*Tfm^2)/(df*Vf)...
    +(1-t)*dt*P1(i)*(a0*1e-4+a1*1e-7*Tfm+a2*Tfm^2)/(df*Vf);
Tmcal=Tm+dt*(A*(c0+c1*Tfm+c2*Tfm^2)*(Tfm-Tm)+P1(i)*t-...
(m0+m1*Tm+m2*Tm^2)*(d0+d1*Tm+d2*Tm^2)*2*(Tm-Tpool))/...
((g0+g1*Tm+g2*Tm^2)*(d0+d1*Tm+d2*Tm^2)*Vm);
F1=1-A*dt*(b0*1e-1+2*b1*1e-4*Tfm+3*b2*Tfm^2)/(df*Vf)...
+A*dt*Tm*(b1*1e-4+2*b2*Tfm)/(df*Vf)+dt*(1-t)*P1(i)*(a1*1e-7+2*a2*Tfm)/(df*Vf);
F2=A*dt*1e-1*(Tm-Tfm)/(df*Vf);
F3=A*dt*1e-4*(Tm*Tfm-Tfm^2)/(df*Vf);
F4=(1-t)*P1(i)*dt*1e-4/(df*Vf);
F=[F1 F2 F3 F4;0 1 0 0;0 0 1 0;0 0 0 1];
if j==3001
E1=inv(F'*F);
j=0;
else
Ea=E-E*H*(inv(H'*E*H+1e-15))*H'*E;
E1=F*Ea*F';
end
E=E1;
Tm=Tmcal;
Tfm=Tfm1;
if i<100
P=P+3.997e4;
P1(1+i)=P;
else
P=4e6;
P1(1+i)=P;
end
end
```


Feedback Reactivity - Model and Actual
Reactivity (Beta)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
0
20
40
60
80
100
120
140
160
Time (seconds)

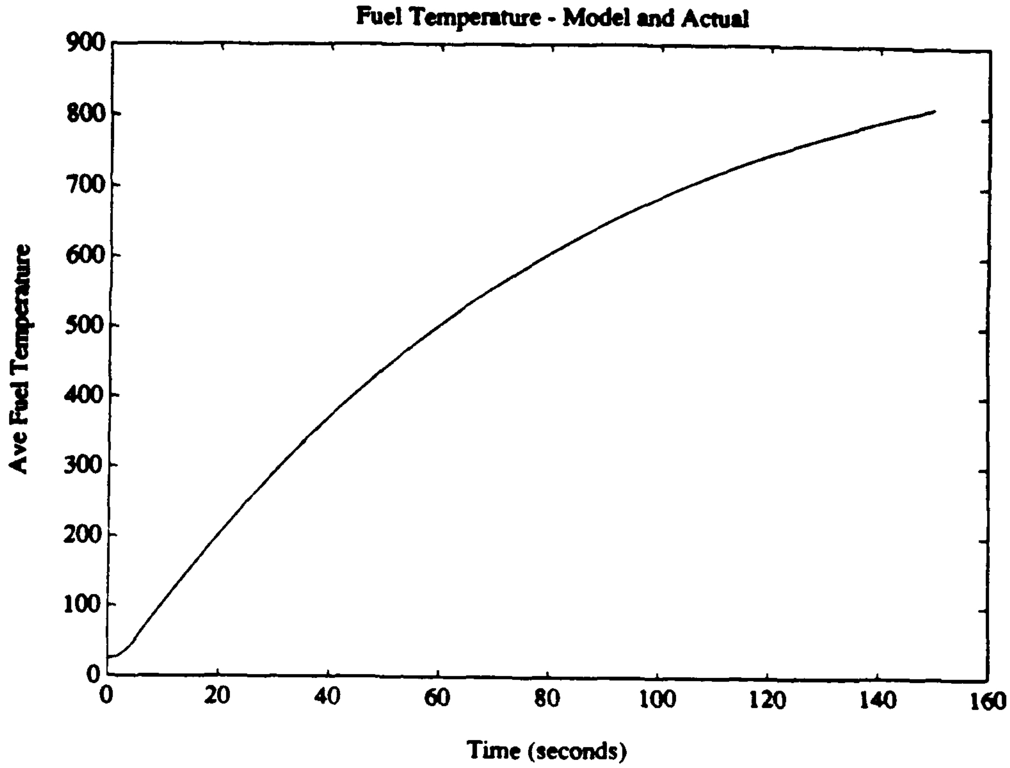

Feedback Reactivity - Model
Reactivity (Beta)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
0
20
40
60
80
100
120
140
160
Time (seconds)

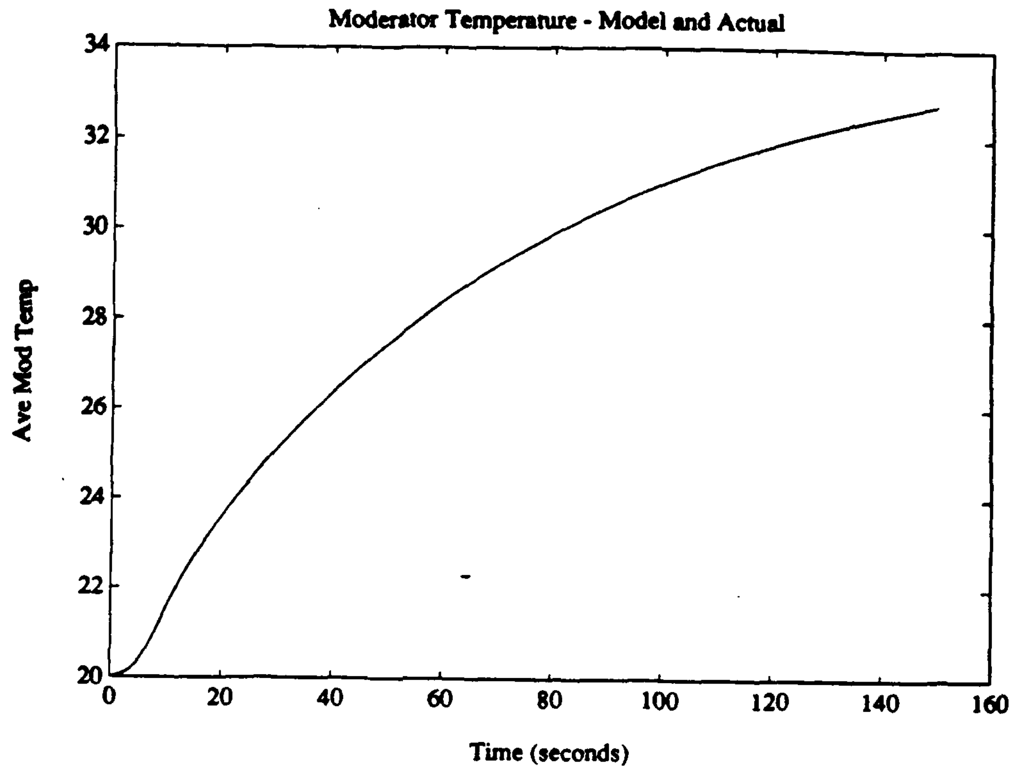

Estimated Model Parameters
a0 b0 b1
10
8
6
4
2
0
-2
0
20
40
60
80
100
120
140
160
Time (seconds)


Average Model Parameters
a0 b0 b1
Time (seconds)
10
8
6
4
2
0
-2
0
20
40
60
80
100
120
140
160



x10⁶
Reactor Power
Power - watts
Time (seconds)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
20
40
60
80
100
120
140
160


Fuel Temperature - Model and Actual
Ave Fuel Temperature
Time (seconds)
0
100
200
300
400
500
600
700
800
900
0
20
40
60
80
100
120
140
160

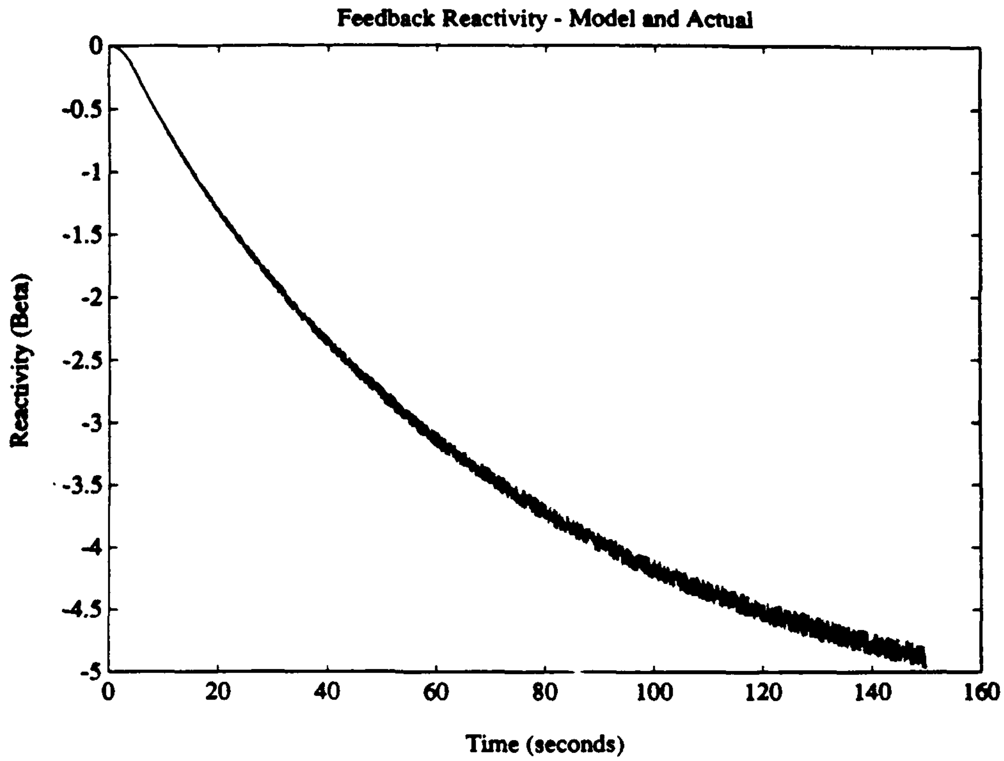

Moderator Temperature - Model and Actual
Ave Mod Temp
Time (seconds)
34
32
30
28
26
24
22
20
0
20
40
60
80
100
120
140
160

```
a0=9.8218e-4;
a1=-4.0822e-7;
a2=1.1773e-10;
b0=1.113e-1;
b1=1.5402e-4;
b2=-4.0805e-8;
c0=78.381;
c1=0.3393;
c2=-8.9181e-5;
d0=4189.8;
d1=-0.61063;
d2=0.0088811;
g0=1002.9;
g1=-0.1599;
g2=-0.0028345;
m2=-0.0151;
m1=2.9305;
m0=-49.79;
A=14.0;
df=3550;
Vf=0.09866089;
dt=0.05;
t=6.3e-7;
dm=998.20323;
Vm=0.045434752;
cpm=4182;
Tm=20.0;
Tma(1)=20.0;
Tpool=20.0;
Tfint=25;
Pint=3e3;
Tfr=Tfint;
Tfm=Tfint;
Tfr1(1,1)=Tfm;
P=Pint;
reactfbint=0.0;
for i=1:3000
Tfr1(1,i+1)=Tfr-A*dt*(b0*Tfr+b1*Tfr^2+b2*Tfr^3)/(df*Vf)...
    +A*dt*Tm*(b0+b1*Tfr+b2*Tfr^2)/(df*Vf)...
    +(1-t)*dt*P*(a0+a1*Tfr+a2*Tfr^2)/(df*Vf);
heatin=dt*((A*(c0+c1*Tfr+c2*Tfr^2)*(Tfr-Tm))+(t*P))/...
((g0+g1*Tm+g2*Tm^2)*(d0+d1*Tm+d2*Tm^2)*Vm);
heatout=dt*(m0+m1*Tm+m2*Tm^2)*2*(Tm-Tpool)/((g0+g1*Tm+g2*Tm^2)*Vm);
Tma(i+1)=heatin-heatout+Tm;
Tm=Tma(i+1);
Tfr=Tfr1(1,i+1);
if i<100
P=P+3.997e4;
else
P=4e6;
end
end
for i=1:3000
 reactfb(1,i)=(Tfr1(1,i)-Tfint)*(-3.85-(730/(273.15+Tfr1(1,i))))*1e-5/0.0073;
```

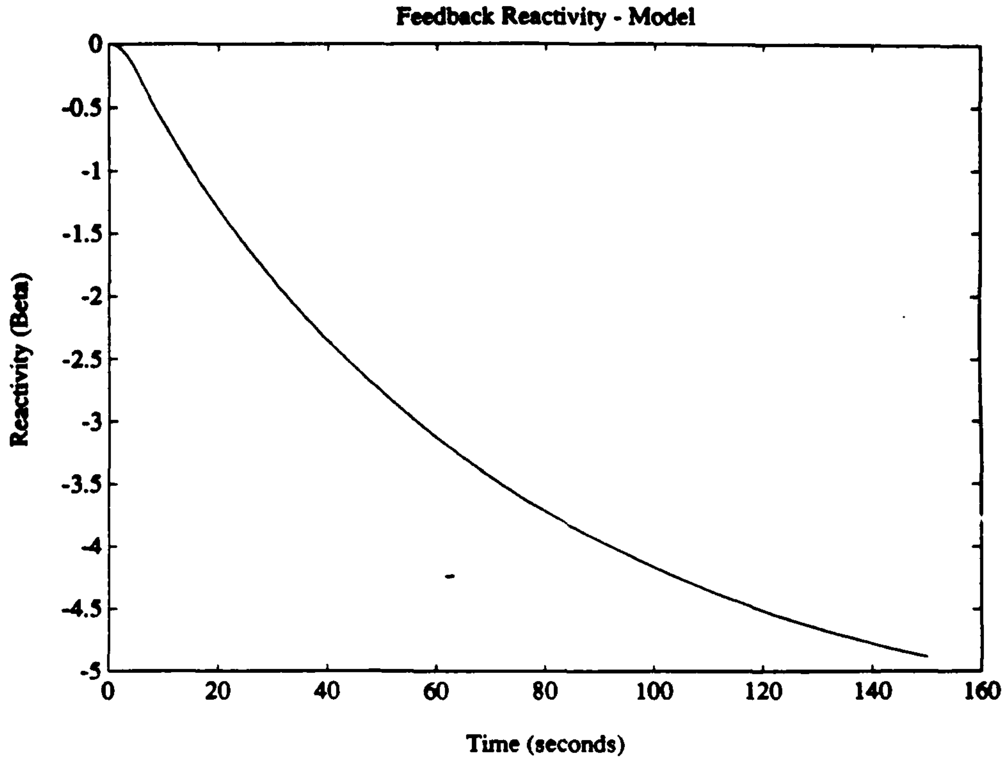
```
end
for i=1:3000
  reactfb(1,i)=reactfb(1.i)+0.02*reactfb(1.i)*(1-2*rand);
end
```

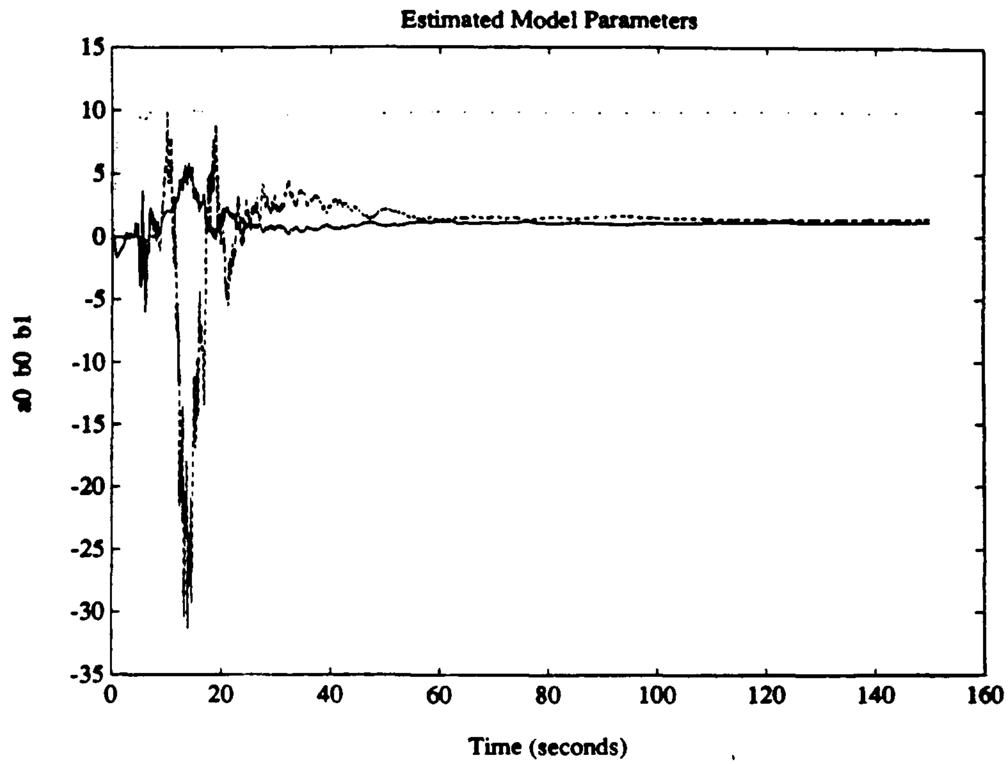
```
a0=0;
a1=-4.0822;
a2=1.1773e-10::
b0=0;
b1=0;
b2=-4.0805e-8;
c0=78.381;
c1=0.3393;
c2=-8.9181e-5;
do=4189.8;
d1=-0.61063;
d2=0.0088811;
g0=1002.9;
g1=-0.1599;
g2=-0.0028345;
m0=-49.79;
m1=2.9305;
m2=-0.0151;
A=14.0;
df=3550;
Vf=0.09866089;
dt=0.05;
t=6.3e-7;
dm=998.20323;
Vm=0.045434752;
cpm=4182;
Tm=20.0;
Tm1(1)=Tm;
Tpool=20.0;
Tfint=25;
Pint=3e3;
reactfbm(1)=0.0;
Tfm=Tfint;
P=Pint;
P1(1)=Pint;
datam=[Tfm b0 b1 a0];
F1=1-A*dt*(b0*1e-1+2*b1*1e-4*Tfm+3*b2*Tfm^2)/(df*Vf)...
+A*dt*Tm*(b1*1e-4+2*b2*Tfm)/(df*Vf)+dt*(1-t)*P*(a1*1e-7+2*a2*Tfm)/(df*Vf);
F2=A*dt*1e-1*(Tm-Tfm)/(df*Vf);
F3=A*dt*1e-4*(Tm*Tfm-Tfm^2)/(df*Vf);
F4=(1-t)*P*dt*1e-4/(df*Vf);
F=[F1 F2 F3 F4;0 1 0 0;0 0 1 0;0 0 0 1];
E=inv(F'*F);
j=0.0;
sumi=0.0;
b0sum=0.0;
b0ave(1)=0.0;
b1sum=0.0;
b1ave(1)=0.0;
a0sum=0.0;
a0ave(1)=0.0;
for i=1:3000
X=[Tfm b0 b1 a0]';
h=(-3.85+730*Tfm/(273.15+Tfm)^2-730/(273.15+Tfm)-730*Tfint/(273.15+Tfm)^2...
```

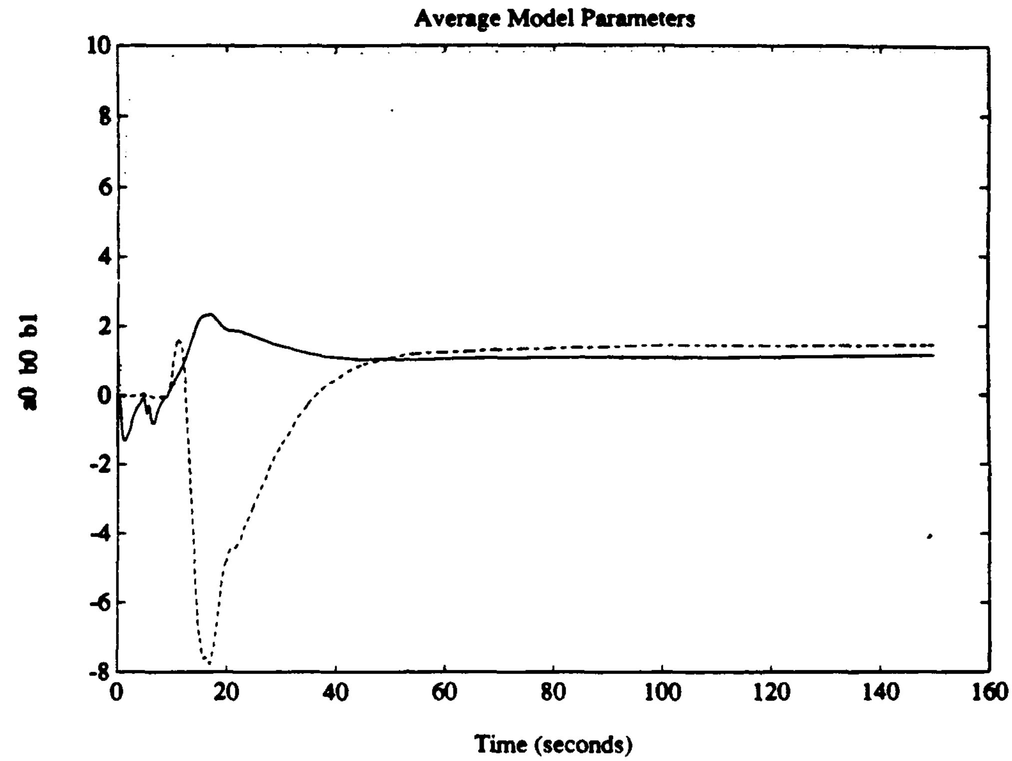
```
 )*1e-5/.0073;
H=[h 0 0 0]';
O=H'*E*H+1e-7;
L=E*H*inv(O);
Y=reactfb(1,i);
xhat=X+L*(Y-(Tfm-Tfint)*(-3.85-(730/(273.15+Tfm)))*1e-5/.0073);
datam=[datam;xhat'];
Tfm=xhat(1,1);
reactfbm(i+1)=(Tfm-Tfint)*(-3.85-(730/(273.15+Tfm)))*1e-5/.0073;
Tm1(i+1)=Tm;
b0=xhat(2,1);
b1=xhat(3,1);
a0=xhat(4,1);
b0sum=b0*i+b0sum;
b1sum=b1*i+b1sum;
a0sum=a0*i+a0sum;
sumi=i+sumi;
b0ave(i+1)=b0sum/sumi;
b1ave(i+1)=b1sum/sumi;
a0ave(i+1)=a0sum/sumi;
j=j+1;
Tfm1=Tfm-A*dt*(b0*1e-1*Tfm+b1*1e-4*Tfm^2+b2*Tfm^3)/(df*Vf)...
    +A*dt*Tm*(b0*1e-1+b1*1e-4*Tfm+b2*Tfm^2)/(df*Vf)...
    +(1-t)*dt*P1(i)*(a0*1e-4+a1*1e-7*Tfm+a2*Tfm^2)/(df*Vf);
Tmcal=Tm+dt*(A*(c0+c1*Tfm+c2*Tfm^2)*(Tfm-Tm)+P1(i)*t-...
(m0+m1*Tm+m2*Tm^2)*(d0+d1*Tm+d2*Tm^2)*2*(Tm-Tpool))/...
((g0+g1*Tm+g2*Tm^2)*(d0+d1*Tm+d2*Tm^2)*Vm);
F1=1-A*dt*(b0*1e-1+2*b1*1e-4*Tfm+3*b2*Tfm^2)/(df*Vf)...
+A*dt*Tm*(b1*1e-4+2*b2*Tfm)/(df*Vf)+dt*(1-t)*P1(i)*(a1*1e-7+2*a2*Tfm)/(df*Vf);
F2=A*dt*1e-1*(Tm-Tfm)/(df*Vf);
F3=A*dt*1e-4*(Tm*Tfm-Tfm^2)/(df*Vf);
F4=(1-t)*P1(i)*dt*1e-4/(df*Vf);
F=[F1 F2 F3 F4;0 1 0 0;0 0 1 0;0 0 0 1];
if j==3001
E1=inv(F'*F);
j=0;
else
Ea=E-E*H*(inv(H'*E*H+1e-7))*H'*E;
E1=F*Ea*F';
end
E=E1;
Tm=Tmcal;
Tfm=Tfm1;
if i<100
P=P+3.997e4;
P1(1+i)=P+.02*P*(1-2*rand);
else
P=4e6;
P1(1+i)=P+.02*P*(1-2*rand);
end
end
```

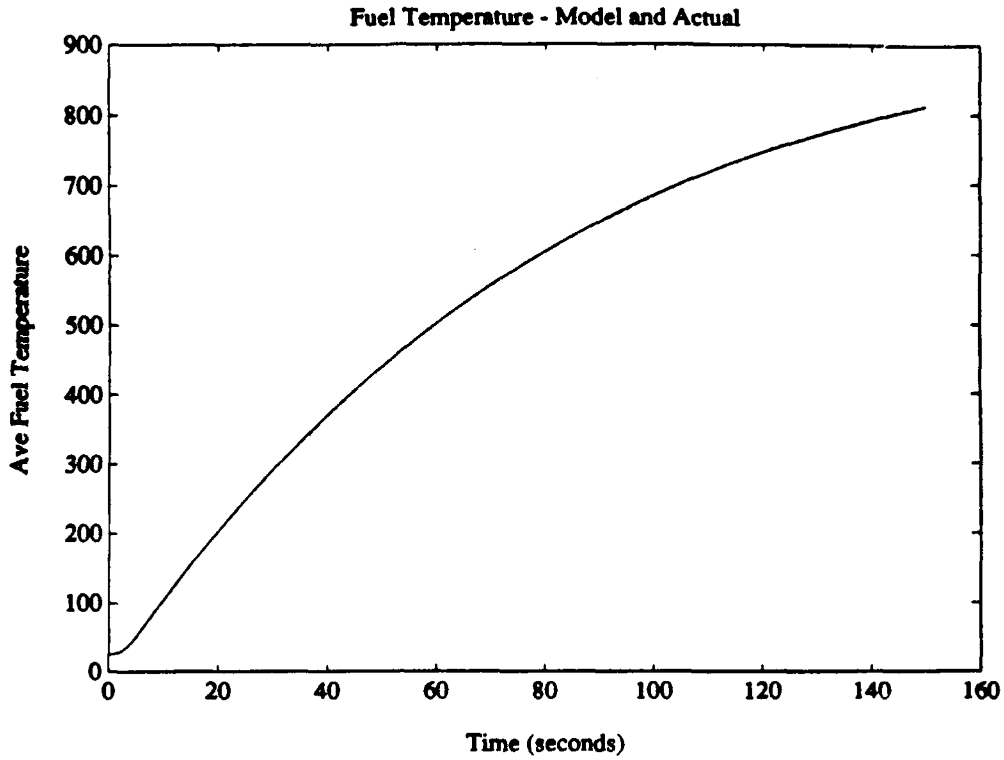


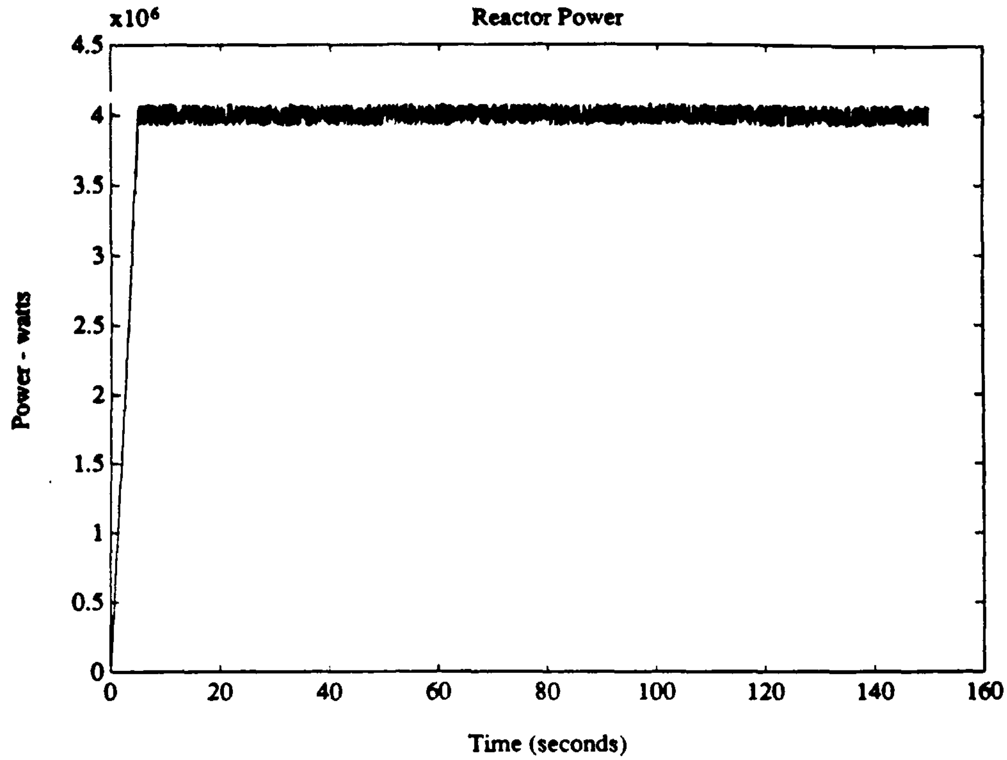
Feedback Reactivity - Model and Actual
Reactivity (Beta)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
0
20
40
60
80
100
120
140
160
Time (seconds)

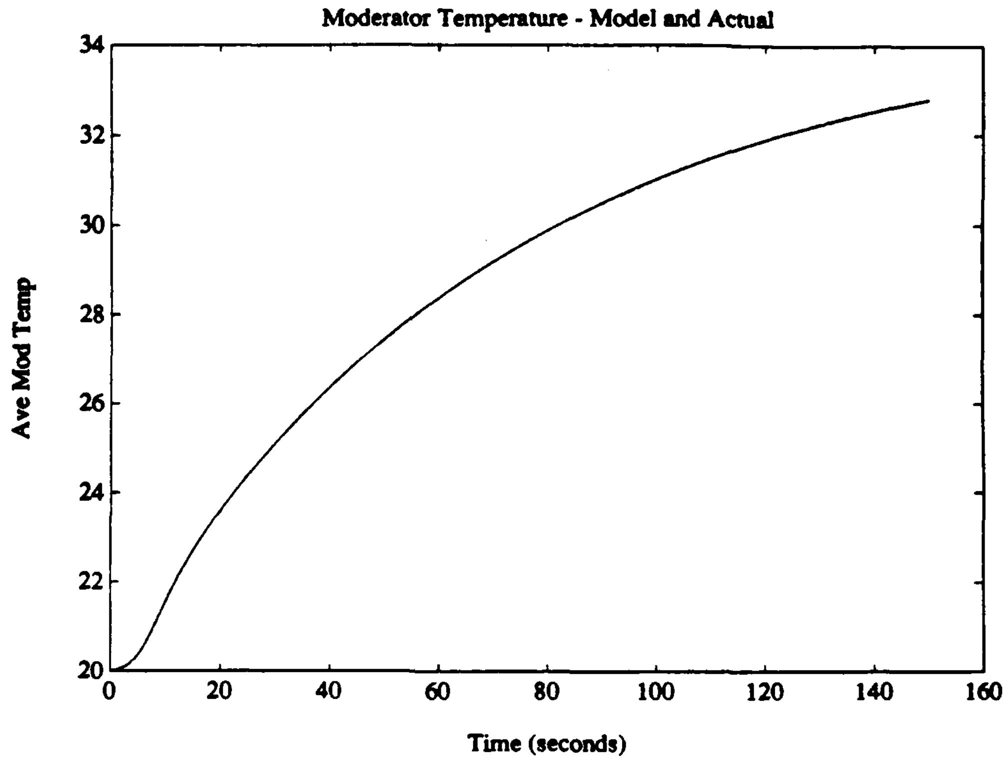

Feedback Reactivity - Model
Reactivity (Beta)
Time (seconds)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
0
20
40
60
80
100
120
140
160


Estimated Model Parameters
a0 b0 b1
Time (seconds)
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
0
20
40
60
80
100
120
140
160


Average Model Parameters
a0 b0 b1
10
8
6
4
2
0
-2
-4
-6
-8
0
20
40
60
80
100
120
140
160
Time (seconds)


Fuel Temperature - Model and Actual
Ave Fuel Temperature
Time (seconds)
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160


Reactor Power
x10^6
Power - watts
Time (seconds)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
20
40
60
80
100
120
140
160


Moderator Temperature - Model and Actual
Ave Mod Temp
Time (seconds)
34
32
30
28
26
24
22
20
0
20
40
60
80
100
120
140
160

```
t2=1:1:3000;
plot(t2/20,datam(t2,2),t2/20,datam(t2,3),t2/20,datam(t2,4))
title('Estimated Model Parameters')
ylabel('a0  b0  b1')
xlabel('Time (seconds)')
print('oe')
plot(t2/20,b0ave(t2),t2/20,b1ave(t2),t2/20,a0ave(t2))
title('Average Model Parameters')
ylabel('a0  b0  b1')
xlabel('Time (seconds)')
print('oe')
plot(t2/20,Tfr1(1,t2),t2/20,datam(t2,1))
title('Fuel Temperature - Model and Actual')
ylabel('Ave Fuel Temperature')
xlabel('Time (seconds)')
print('oe')
plot(t2/20,P1(t2))
title('Reactor Power')
ylabel('Power - watts')
xlabel('Time (seconds)')
print('oe')
plot(t2/20,reactfb(1,t2),t2/20,reactfbm(t2))
title('Feedback Reactivity - Model and Actual')
ylabel('Reactivity (Beta)')
xlabel('Time (seconds)')
print('oe')
plot(t2/20,reactfbm(t2))
title('Feedback Reactivity - Model')
ylabel('Reactivity (Beta)')
xlabel('Time (seconds)')
print('oe')
plot(t2/20,Tma(t2),t2/20,Tm1(t2))
title('Moderator Temperature - Model and Actual')
ylabel('Ave Mod Temp')
xlabel('Time (seconds)')
print('oe')
```

```
t2=1:1:3000;
plot(t2/20.datam(t2.2),t2/20.datam(t2.3).t2/20.datam(t2,4))
title('Estimated Model Parameters')
ylabel('a0 b0 b1')
xlabel('Time (seconds)')
pause
plot(t2/20,b0ave(t2).t2/20.b1ave(t2).t2/20,a0ave(t2))
title('Average Model Parameters')
ylabel('a0 b0 b1')
xlabel('Time (seconds)')
pause
plot(t2/20,Tfr1(1,t2),t2/20,datam(t2,1))
title('Fuel Temperature - Model and Actual')
ylabel('Ave Fuel Temperature')
xlabel('Time (seconds)')
pause
plot(t2/20,P1(t2))
title('Reactor Power')
ylabel('Power - watts')
xlabel('Time (seconds)')
pause
plot(t2/20.reactfb(1.t2).t2/20.reactfbm(t2))
title('Feedback Reactivity - Model and Actual')
ylabel('Reactivity (Beta)')
xlabel('Time (seconds)')
pause
plot(t2/20.reactfbm(t2))
title('Feedback Reactivity - Model')
ylabel('Reactivity (Beta)')
xlabel('Time (seconds)')
pause
plot(t2/20.Tma(t2).t2/20.Tm1(t2))
title('Moderator Temperature - Model and Actual')
ylabel('Ave Mod Temp')
xlabel('Time (seconds)')
pause
```

Appendix D

```
c This program runs the heat deposition model for reactivity
c using a specified input file containing time(s), power(kW)
c inverse kinetics reactivity(millibeta). transient rod bank
c heigth(units). Formulation is for the ACRR.
c
c234567-----------------------------------------------
      real a0, a1, b0, b1, b2, c0, c1, c2, d0, d1. d2, g0, g1, g2, m0
     @, m1, m2, Af, df, Vm, Cpm, TM, Tpool, Tfint, Pwr, Dkfb, dt, t,
     @dm, Vf, Tfm, htrb, invk, Dkbal, bound, time, OM, Y, Dkest, OM2
     @,HP1, dev, HP2, a2, Pin, Tmcal, Tfmcal, htrbint, b, invk1, invks
      real F(4,4), E(4,4), X(4,1), H(4,1), HT(1,4), OM1(4,1), L1(4.1)
     @, XHAT(4,1), L(4,1), HTE(1,4), EP(4,4), EA(4,4), HTE1(1,4),
     @EA1(4,4), FT(4,4), FTF(4,4), BB(4,4)
      logical align
      Integer rods, R
      common/area1/a0, a1, a2, b0, b1, b2, c0, c1, c2, d0, d1, d2, g0,
     @ g1, g2, m0, m1, m2, Af, df, Vm, Cpm, TM, Tpool, Tfint, Pwr, dt,
     @ Dkfb, t, dm, Vf, Tfm, htrb, invk, Dkbal, bound, time, OM, Y,
     @ Dkest, OM2, HP1, HP2, dev, pin, Tmcal, Tfmcal, htrbint
      common/area2/E, X, H, HT, OM1, L1, XHAT, L, HTE, EP, EA,
     @ HTE1, EA1, FT, FTF, BB, F
c
c initialize parameters
c
      a0=9.8
      a1=-4.0822
      a2=1.1773E-10
      b0=-19.0
      b1=54.8
      b2=-4.0805E-8
      c0=78.381
      c1=0.3393
      c2=-8.9181E-5
      d0=4189.8
      d1=-0.61063
      d2=0.0088811
      g0=1002.9
      g1=-0.1599
      g2=-0.0028345
      m0=-49.79
      m1=2.9305
      m2=-0.0151
      Af=14.0
      df=3550.0
      Vm=0.045434752
      Cpm=4182.0
      TM=20.0
      Tpool=20.0
      Tfint=23.0
      Pwr=2.57E3
      Dkfb=0.0
      dt=0.045
      t=6.3E-7
      dm=998.20323
```

```
      Vf=0.09866089
      Tfm=Tfint
      htrb=3003.0
      htrbint=3003.0
      invk=0.0
      Dkbal=0.0
      align=.false.
      bound=0.02
      b=bound
      time=0.0
      F(1,1)=1-Af*dt*(b0*1E-1+2.0*b1*1E-4*Tfm+3.0*b2*Tfm**2)/(df*Vf)
     @+Af*dt*Tm*(b1*1E-4+2.0*b2*Tfm)/(df*Vf)+dt*(1-t)*Pwr*(a1*1E-7+
     @2.0*a2*Tfm)/(df*Vf)
      F(1,2)=Af*dt*1E-1*(Tm-Tfm)/(df*Vf)
      F(1,3)=Af*dt*1E-4*(Tm*Tfm-Tfm**2)/(df*Vf)
      F(1,4)=(1-t)*Pwr*dt*1E-4/(df*Vf)
      F(2,1)=0.0
      F(2,2)=1.0
      F(2,3)=0.0
      F(2,4)=0.0
      F(3,1)=0.0
      F(3,2)=0.0
      F(3,3)=1.0
      F(3,4)=0.0
      F(4,1)=0.0
      F(4,2)=0.0
      F(4,3)=0.0
      F(4,4)=1.0
      call Transmat(F,FT,4,4)
      call Matmult(FT,4,4,F,4,4,FTF)
      E(1,1)=1.0
      E(1,2)=0.0001
      E(1,3)=0.000025
      E(1,4)=-0.000042
      E(2,1)=0.0001
      E(2,2)=1.0
      E(2,3)=0.0
      E(2,4)=0.0
      E(3,1)=0.000025
      E(3,2)=0.0
      E(3,3)=1.0
      E(3,4)=0.0
      E(4,1)=-0.000043
      E(4,2)=0.0
      E(4,3)=0.0
      E(4,4)=1.0
      invk1=invk
  100 invks=(invk1+invk)/2.0
      Dkest=validate(invk, invks, Dkbal,b)
      print*, time, Dkest, Tfm
      IF (align) THEN
        call Estmodel
      end IF
      call Advmodel
```

```
      Dkfb=reactfb(Tfm,Tfint)
      Read *, time, Pin, R, rods
      Pwr=Pin*1E3
      invk1=invk
      invk=real(R)*0.001
      htrb=real(rods)
      Dkbal=Dkfb-reactr(htrb)/100.0+reactr(htrbint)/100.0
      GO TO 100
 1000 end
c
c
      subroutine Advmodel
c
      common/area1/a0, a1, a2, b0, b1, b2, c0, c1, c2, d0, d1, d2, g0,
     @ g1, g2, m0, m1, m2, Af, df, Vm, Cpm, TM, Tpool, Tfint, Pwr, dt,
     @ Dkfb, t, dm, Vf, Tfm, htrb, invk, Dkbal, bound, time, OM, Y,
     @ Dkest, OM2, HP1, HP2, dev, pin, Tmcal, Tfmcal, htrbint
      common/area2/E(4,4), X(4,1), H(4,1), HT(1,4), OM1(4,1), L1(4,1)
     @, XHAT(4,1), L(4,1), HTE(1,4), EP(4,4), EA(4,4), HTE1(1,4),
     @EA1(4,4), FT(4,4), FTF(4,4), BB(4,4), F(4,4)
c
      Tfmcal=Tfm-Af*dt*(b0*1E-1*Tfm+b1*1E-4*Tfm**2+b2*Tfm**3)/(df*Vf)
     @+Af*dt*Tm*(b0*1E-1+b1*1E-4*Tfm+b2*Tfm**2)/(df*Vf)+(1-t)*dt*Pwr*
     @(a0*1E-4+a1*1E-7*Tfm+a2*Tfm**2)/(df*Vf)
c     Tmcal=Tm+dt*(Af*(c0+c1*Tfm+c2*Tfm**2)*(Tfm-Tm)+Pwr*t-(m0+m1*Tm+
c    @m2*Tm**2)*(d0+d1*Tm+d2*Tm**2)*2.0*(Tm-Tpool))/((go+g1*Tm+g2*
c    @Tm**2)*(d0+d1*Tm+d2*Tm**2)*Vm)
      F(1,1)=1-Af*dt*(b0*1E-1+2.0*b1*1e-4*Tfm+3.0*b2*Tfm**2)/(df*Vf)+
     @Af*dt*Tm*(b1*1E-4+2.0*b2*Tfm)/(df*Vf)+dt*(1-t)*Pwr*(a1*1E-7+2.0
     @*a2*Tfm)/(df*Vf)
      F(1,2)=Af*dt*1E-1*(Tm-Tfm)/(df*Vf)
      F(1,3)=Af*dt*1E-4*(Tm*Tfm-Tfm**2)/(df*Vf)
      F(1,4)=(1-t)*Pwr*dt*1E-4/(df*Vf)
      H(1,1)=(-3.85+730.0*Tfm/(273.15+Tfm)**2-730.0/(273.15+Tfm)-
     @730.0*Tfint/(273.15+Tfm)**2)*1E-5/0.0073
      HT(1,1)=H(1,1)
      call Matmult(HT,1,4,E,4,4,HTE)
      call Matmult(HTE,1,4,H,4,1,HP1)
      HP2=-1.0/(HP1+1E-7)
      call Multscale(HTE,HTE1,HP2,1,4)
      call Matmult(H,4,1,HTE1,1,4,EP)
      call Matmult(E,4,4,EP,4,4,EA)
      call Addmat(E,EA,EA1,4,4)
      call Transmat(F,FT,4,4)
      call Matmult(EA1,4,4,FT,4,4,FTF)
      call Matmult(F,4,4,FTF,4,4,E)
      Tfm=Tfmcal
c     Tm=Tmcal
      return
      end
c
c
      subroutine Estmodel
c
```

```
      common/area1/a0, a1, a2, b0, b1, b2, c0, c1, c2, d0, d1, d2, g0,
     @ g1, g2, m0, m1, m2, Af, df, Vm, Cpm, TM, Tpool, Tfint, Pwr, dt,
     @ Dkfb, t, dm, Vf, Tfm, htrb, invk, Dkbal, bound, time, OM, Y,
     @ Dkest, OM2, HP1, HP2, dev, pin, Tmcal, Tfmcal, htrbint
      common/area2/E(4,4), X(4,1), H(4,1), HT(1,4), OM1(4,1), L1(4,1)
     @, XHAT(4,1), L(4,1), HTE(1,4), EP(4,4), EA(4,4), HTE1(1,4),
     @EA1(4,4), FT(4,4), FTF(4,4), BB(4,4), F(4,4)
c
      X(1,1)=Tfm
      X(2,1)=b0
      X(3,1)=b1
      X(4,1)=a0
      H(1,1)=(-3.85+730.0*Tfm/(273.15+Tfm)**2-730.0/(273.15+Tfm)-
     @730.0*Tfint/(273.15+Tfm)**2)*1E-5/0.0073
      HT(1,1)=H(1,1)
      H(2,1)=0.0
      H(3,1)=0.0
      H(4,1)=0.0
      Y=Dkest+reactr(htrb)/100.0-reactr(htrbint)/100.0
      HT(1,2)=0.0
      HT(1,3)=0.0
      HT(1,4)=0.0
      call Matmult(E,4,4,H,4,1,OM1)
      call Matmult(HT,1,4,OM1,4,1,OM)
      OM=OM+1E-7
      OM2=1.0/OM
      call Multscale(OM1,L,OM2,4,1)
      dev=(Y-(Tfm-Tfint)*(-3.85-(730.0/(273.15+Tfm)))*1E-5/0.0073)
      call Multscale(L,L1,dev,4,1)
      call Addmat(X,L1,XHAT,4,1)
      Tfm=XHAT(1,1)
      b0=XHAT(2,1)
      b1=XHAT(3,1)
      a0=XHAT(4,1)
      return
      end
c
c
      subroutine Addmat(A,B,C,N,M)
c
      Integer N,M,i,j
      real A(N,M), B(N,M), C(N,M)
      Do 10, i=1,N
        Do 10, j=1,M
 10       C(i,j)=A(i,j)+B(i,j)
      return
      end
c
c
      subroutine Transmat(A,C,N,M)
c
      Integer N,M,i,j
      real A(N,M), C(N,M)
      Do 20, i=1,N
```

```
      Do 20, j=1,M
 20       C(i,j)=A(j,i)
    return
    end
c
c
    subroutine Multscale(A,C,b,N,M)
c
    Integer N,M,i,j
    real A(N,M), C(N,M), b
    Do 30, i=1,N
      Do 30, j=1,M
 30       C(i,j)=b*A(i,j)
    return
    end
c
c
    subroutine Matmult(A,N,M,B,M,k,C)
c
    Integer i,j,w,N,M,k
    real A(N,M), B(M,k), C(N,k), sum
    Do 50, i=1,N
      do 50, j=1,k
        sum=0.0
        Do 40, w=1,M
          sum=sum+A(i,w)*B(w,j)
 40         continue
          C(i,j)=sum
 50         continue
    return
    end
c
c
c
    real function reactr(p)
c
    real p
    if(p .lt. 2031.) p=2031.
    if(p .gt. 7460.) p=7460.
    if(p .le. 2700.) go to 600
    if(p .le. 3100.) go to 605
    if(p .le. 3300.) go to 610
    if(p .le. 3500.) go to 615
    if(p .le. 3700.) go to 620
    if(p .le. 3900.) go to 625
    if(p .le. 4100.) go to 630
    if(p .le. 4300.) go to 635
    if(p .le. 4500.) go to 640
    if(p .le. 4700.) go to 645
    if(p .le. 4900.) go to 650
    if(p .le. 5100.) go to 655
    if(p .le. 5300.) go to 660
    if(p .le. 5500.) go to 665
    if(p .le. 5700.) go to 670
```

```
      if(p .le. 5900.) go to 675
      if(p .le. 6100.) go to 680
      if(p .le. 6300.) go to 685
      if(p .le. 6700.) go to 690
      if(p .le. 7100.) go to 695
      if(p .le. 7500.) go to 700
      go to 705
600   reactr=-0.016143*p+472.985693
      return
605   reactr=-0.049250*p+562.375
      return
610   reactr=-0.0765*p+646.85
      return
615   reactr=-0.091*p+694.7
      return
620   reactr=-0.1005*p+727.9
      return
625   reactr=-0.1085*p+757.5
      return
630   reactr=-0.1225*p+812.15
      return
635   reactr=-0.125*p+822.4
      return
640   reactr=-0.1305*p+846.05
      return
645   reactr=-0.1295*p+841.55
      return
650   reactr=-0.1295*p+841.55
      return
655   reactr=-0.122*p+804.8
      return
660   reactr=-0.120*p+794.6
      return
665   reactr=-0.110*p+741.6
      return
670   reactr=-0.1065*p+722.35
      return
675   reactr=-0.0965*p+665.35
      return
680   reactr=-0.097*p+668.3
      return
685   reactr=-0.076*p+540.2
      return
690   reactr=-0.06575*p+475.625
      return
695   reactr=-0.04725*p+351.675
      return
700   reactr=-0.028*p+215.0
      return
705   reactr=-0.00333*p+30.0
      return
      end
c
c
```

```fortran
      real function reactfb(T,TIN)
c
      real T,TIN,TK
      TK=T+273.15
      reactfb=(T-TIN)*(-3.85-730.0/TK)*1E-5/0.0073
      return
      end
c
c
      real function validate(ma,mb,mc,b)
c
      real m(3), N(3), PAR, TEST, m2(2), N2(2),b
      real ma,mb,mc
      integer i,k
      m(1)=ma
      m(2)=mb
      m(3)=mc
      Do 10, i=1,3
        N(i)=ABS(m(i)-(m(1)+m(2)+m(3))/3.0)
10    continue
      TEST=(8.0/3.0)*((m(1)*b)**2)
      PAR=abs(N(1)**2+N(2)**2+N(3)**2-(9.0*N(1)**2)/2.0)
      if(PAR .lt. TEST) THEN
        validate=(m(1)+m(2)+m(3))/3.0
        go to 100
      end if
      if(N(1) .gt. N(2)) THEN
        if(N(1) .gt. N(3)) THEN
          m2(1)=m(2)
          m2(2)=m(3)
        else
          m2(1)=m(1)
          m2(2)=m(2)
        end if
      else
        if(N(2) .gt. N(3)) THEN
          m2(1)=m(1)
          m2(2)=m(3)
        else
          m2(1)=m(1)
          m2(2)=m(2)
        end if
      end if
      Do 40, k=1,2
        N2(k)=abs(m2(k)-(m2(1)+m2(2))/2.0)
40    continue
      TEST=2.0*((b*m(1))**2)
      PAR=abs(N2(1)**2+N2(2)**2-4.0*N2(1)**2)
      if(PAR .lt. TEST) THEN
        validate=(m2(1)+m2(2))/2.0
        go to 100
      else
        validate=m(1)
      end if
```

```
100 return
    end
```

FORTRAN Code Variables for Model Implimentation

a_o, a_1, a_2 — Polynomial coefficient for a second order polynomialrepresnting the inverse of the fuel specific heat capacity.

b_o, b_1, b_2 — Polynomial coefficients for a second order Polynomial representing the overall fuel to coolant heat transfer coefficient divided by the fuel specific heat capacity.

C_o, C_1, C_2 — Polynomial coefficients for a second order Polynomial representing the overall fuel to coolant heat transfer coefficient.

d_o, d_1, d_2 — Polynomial coefficients for a second order polynomial the moderator specific heat capacity.

g_o, g_1, g_2 — Polynomial coefficients for a second order polynomial representing the moderator density (Main, Advmodel, Estmodel).

m_o, m_1, m_2 — Polynomial coefficients for a second order polynomial representing the moderator mass flow rate.

Af — fuel to coolant heat transfer surface area.

df — fuel density

V_m	Volume of moderator within the core.
C_{pm}	Specific heat capacity of moderator.
T_m	Moderator average temperature.
T_{pool}	Reactor pool temperature.
T_{fint}	Initial fuel temperature.
PWR	Reactor Power.
DKfb	Thermal feedback reactivity.
dt	Sample time.
t	Percentage of fission power deposition in the coolant due to gamma heating.
V_f	Fuel volume.
T_{fm}	Fuel temperature as perdicted by thermal model.

htrb	Transient rod bank position.
invk	Reactivity calculated via Inverse Kinetics.
DKbal	Reactivity calculated via reactivity balance.
bound	Percentage error bound of reactivity signals for use in signal validation.
time	Elapsed time since start of transient.
OM	Value used in calculation of estimation routine Kalman gain.
Y	Estimation routine value of actual reactor reactivity equal to the validated reactivity signal.
DKest	Value of the validated reacivity signal.
dev	Estimation routine value of innovation equal to the difference between actual and estimated reactivity.
P_{in}	Initial reactor power.
Tmcal	Perdicted moderator temperature for next time step.

htrbint	Initial position of transient rod bank.
b	Percentage error bound of reactivity signals for use in signal validation.
Invk1	Inverse Kinetics reactivity from previous step inverse kinetics reactivity.
F	Linearized system matrix for model parameter estimation.
F^t	Transpose of matrix F.
E	System error covariance matrix for model parameter estimation.
X	Present value of model fuel temperature, and model thermal parameter coefficients b_0, b_1, and a_0.
H	System descriptive matrix.
HT	Transpose of matrix H.
R	Interger value of input inverse kinetics reactivity as read from input file.
XHAT	Estimation values of fuel temperature, and model thermal parameter coefficients, b_0, b_1, a_0.

L	Matrix representing Kalman estimation gain.
Align	Logical varible used to determine it estimation routine should be used. True = Estimate new model parameter coefficients. False = Use present values of model coefficients.
A,B,C,N,M	Matrix values used in matrix math routines.
p	Dummy variable for transient rod position in reactivity function reactor.
T	Dummy variable for fuel temperature in reactivity function reacfb.
T_{in}	Dummy variable for initial fuel temperature in reactivity function reacfb.
TK	Fuel temperature (°K)
M_a, M_b, M_c	Measured reactivity values in reacivity validation routine.
PAR	Value of parity vector magnitude for a reactivity measurement.
Test	Consisting threshold for parity test during reactivity signal validation.

M(1),M(2),M(3)   Measured reactivity values in reacivity validation routine.

OM2, HP1, HP2, HTE, EP, EA, HTE, EA1, FTF, BB are scalar and matrix variables used as intermediate values during parameter calculation.

0.04	2.70	25	3004
0.09	2.80	50	3005
0.13	2.93	127	3006
0.17	3.02	149	3025
0.22	2.58	-16	3082
0.25	2.59	-1	3102
0.3	3.5	277	3129
0.33	3.12	156	3154
0.38	3.23	195	3154
0.42	3.22	185	3166
0.47	3.11	153	3190
0.5	3.48	254	3225
0.53	3.72	295	3255
0.58	2.97	90	3289
0.63	4.99	492	3319
0.67	3.83	267	3346
0.7	4.08	341	3344
0.75	3.89	296	3359
0.8	3.85	286	3388
0.83	5.65	543	3418
0.87	4.48	352	3443
0.92	4.39	358	3445
0.97	4.26	331	3457
1	4.28	332	3487
1.05	4.74	401	3517
1.08	5.43	480	3549
1.13	6.51	562	3593
1.17	6.14	510	3613
1.22	6.77	562	3642
1.25	6.48	522	3675
1.3	7.67	605	3704
1.33	8.49	636	3736
1.38	9.69	675	3766
1.42	8.86	615	3798
1.47	10.83	698	3832
1.5	11.3	694	3865
1.55	12.24	712	3899
1.58	13.59	736	3929
1.63	17.37	794	3971
1.68	22.23	833	3983
1.72	21.48	796	4000
1.77	27.27	848	4008
1.8	29.05	838	4015
1.85	34.5	861	4020
1.88	31.1	809	4023
1.93	35.06	838	4027
1.98	42.63	862	4035
2.02	43.36	842	4037
2.07	52.93	873	4042
2.1	58.63	873	4045
2.15	57.39	849	4047
2.18	68.13	878	4042
2.23	64.7	842	4027
2.27	74.12	865	4043

2.32	82.38	866	4040
2.35	87.86	862	4030
2.4	88.8	849	4035
2.45	95.71	852	4035
2.48	107.16	863	4030
2.53	118.76	865	4030
2.58	106.9	821	4030
2.62	117.27	840	4025
2.67	120.83	831	4027
2.7	122.16	820	4025
2.75	147.35	854	4027
2.8	164.99	857	4032
2.83	166.14	839	4030
2.88	181.68	850	4030
2.92	200.95	857	4018
2.97	197.24	835	4025
3.02	230.9	859	4023
3.05	193.27	786	4025
3.1	223.55	833	4025
3.13	239.3	832	4025
3.18	271.69	847	4025
3.23	288.01	841	4027
3.27	328.78	859	4030
3.32	354.94	855	4030
3.35	390.74	862	4035
3.4	370.11	832	4030
3.45	432.1	857	4030
3.48	436.49	838	4030
3.53	482.29	851	4032
3.57	483.75	834	4032
3.62	447.24	805	4025
3.67	508.3	831	4023
3.7	595.81	854	4037
3.75	582.91	827	4035
3.78	717.44	868	4037
3.83	739.89	849	4037
3.88	779.94	846	4037
3.92	818	842	4035
3.97	882.66	847	4037
4	837.31	815	4037
4.05	973.96	848	4040
4.1	1062.97	847	4035
4.13	1051.06	826	4040
4.18	1135.26	837	4045
4.23	1307.45	853	4042
4.27	1407.67	851	4047
4.32	1436.18	841	4045
4.37	1436.59	827	4045
4.4	1538.31	833	4042
4.45	1649.69	835	4047
4.5	1733.55	831	4050
4.53	1998.42	854	4052
4.58	2010.3	834	4060
4.63	2107.71	832	4055

4.67	2305.83	841	4060
4.72	2387.47	833	4060
4.77	2579.94	837	4067
4.8	2659.68	829	4067
4.85	2851.86	835	4067
4.9	3021.09	832	4069
4.93	3196.9	832	4072
4.98	3358.07	831	4074
5.03	3497.26	826	4077
5.07	3570.52	817	4074
5.12	3651.1	813	4074
5.17	3687.73	803	4072
5.2	3717.03	793	4064
5.25	3746.33	788	4064
5.28	3775.64	779	4060
5.33	3826.92	776	4062
5.38	3922.15	772	4052
5.42	3980.76	766	4062
5.47	4039.36	762	4062
5.5	4046.69	753	4060
5.55	4090.64	750	4060
5.58	4083.32	739	4055
5.63	4105.29	735	4055
5.68	4127.27	728	4055
5.72	4163.9	723	4055
5.77	4149.25	715	4052
5.8	4200.53	712	4050
5.85	4163.9	703	4050
5.88	4149.25	694	4045
5.93	4149.25	690	4047
5.98	4149.25	683	4047
6.02	4149.25	676	4042
6.07	4134.6	670	4047
6.1	4127.27	662	4042
6.15	4119.94	658	4042
6.2	4083.32	648	4037
6.23	4083.32	642	4035
6.28	4039.36	634	4032
6.33	4039.36	629	4032
6.37	4002.73	619	4030
6.42	3973.43	613	4027
6.45	3973.43	608	4030
6.5	3980.76	606	4032
6.55	4017.38	605	4030
6.58	3995.41	597	4032
6.63	3973.43	591	4030
6.67	3973.43	587	4030
6.72	3973.43	584	4032
6.77	3973.43	579	4030
6.8	3966.1	574	4032
6.85	3988.08	574	4032
6.88	3958.78	565	4032
6.93	3929.48	559	4027
6.97	3922.15	554	4025

7.02	3922.15	552	4032
7.07	3944.13	551	4035
7.1	3966.1	550	4037
7.15	3958.78	545	4040
7.18	3966.1	543	4040
7.23	3995.41	544	4052
7.28	3995.41	539	4045
7.32	3995.41	535	4045
7.37	4017.38	535	4047
7.4	3988.08	527	4050
7.45	3973.43	523	4047
7.5	4002.73	524	4050
7.53	4002.73	519	4055
7.58	4010.06	518	4057
7.63	4010.06	514	4055
7.67	4010.06	510	4057
7.72	4039.36	512	4062
7.75	4002.73	503	4062
7.8	4017.38	503	4072
7.83	4002.73	497	4069
7.88	3988.08	493	4072
7.93	3988.08	490	4069
7.97	3988.08	487	4067
8.02	3980.76	484	4067
8.07	3980.76	481	4069
8.1	3995.41	480	4072
8.15	3995.41	478	4069
8.18	3988.08	473	4077
8.23	4002.73	474	4077
8.28	3995.41	469	4073
8.32	3995.41	466	4079
8.37	4017.38	468	4082
8.4	3980.76	459	4077
8.45	3973.43	456	4084
8.48	3958.78	451	4084
8.53	3958.78	450	4092
8.58	3973.43	450	4087
8.62	3966.1	445	4089
8.67	4010.06	451	4092
8.7	3951.45	438	4092
8.75	4002.73	445	4097
8.8	3973.43	437	4099
8.83	3951.45	431	4102
8.88	3966.1	433	4104
8.93	3995.41	435	4102
8.97	3966.1	427	4106
9.02	3980.76	428	4109
9.05	3958.78	422	4111
9.1	3966.1	422	4113
9.13	3944.13	416	4116
9.18	3951.45	416	4116
9.23	3973.43	417	4119
9.27	3973.43	414	4126
9.32	3995.41	416	4126

9.35	3958.78	407	4126
9.4	3966.1	408	4129
9.45	3966.1	406	4131
9.48	3980.76	406	4134
9.53	3980.76	404	4136
9.58	3951.45	397	4136
9.62	3944.13	394	4139
9.67	3951.45	394	4131
9.7	3966.1	394	4143
9.75	3951.45	390	4148
9.78	3922.15	383	4151
9.83	3958.78	389	4151
9.88	3980.76	390	4151
9.92	3980.76	388	4158
9.97	4002.73	390	4163
10	4002.73	388	4166
10.05	3988.08	384	4168
10.1	4024.71	388	4171
10.13	4002.73	381	4173
10.18	3995.41	379	4173
10.23	3980.76	375	4176
10.27	3973.43	372	4176
10.32	3966.1	369	4173
10.35	3973.43	369	4183
10.4	3936.8	361	4188
10.45	3966.1	365	4193
10.48	3980.76	366	4190
10.53	3973.43	363	4195
10.57	3973.43	361	4198
10.62	3944.13	355	4198
10.67	3951.45	355	4203
10.7	3980.76	359	4205
10.75	3973.43	356	4210
10.8	3973.43	354	4205
10.83	3980.76	354	4213
10.88	3980.76	352	4218
10.92	3980.76	351	4220
10.97	3951.45	344	4220
11.02	3973.43	347	4225
11.05	3988.08	348	4218
11.1	3980.76	345	4232
11.15	3980.76	344	4245
11.18	3988.08	343	4237
11.23	3995.41	344	4240
11.27	3988.08	340	4245
11.32	3980.76	338	4242
11.37	3988.08	338	4250
11.4	3988.08	336	4252
11.45	3988.08	335	4255
11.5	4032.04	342	4257
11.53	4010.06	335	4257
11.58	3988.08	331	4262
11.62	3988.08	330	4267
11.67	4002.73	331	4262

11.72	4032.04	335	4274
11.75	4002.73	327	4265
11.8	4032.04	332	4274
11.85	3995.41	324	4282
11.88	4010.06	326	4282
11.93	3995.41	321	4292
11.97	3995.41	320	4292
12.02	4024.71	325	4292
12.07	4010.06	320	4296
12.1	3995.41	316	4296
12.15	3988.08	314	4301
12.18	3995.41	315	4304
12.23	3966.1	308	4306
12.28	4010.06	316	4311
12.32	4002.73	312	4314
12.37	4002.73	311	4314
12.42	3995.41	309	4319
12.45	3980.76	305	4324
12.5	3980.76	304	4324
12.55	3958.78	299	4329
12.58	3988.08	304	4331
12.63	3980.76	301	4338
12.67	3973.43	299	4336
12.72	3995.41	302	4346
12.77	3995.41	301	4341
12.8	3995.41	299	4348
12.85	3988.08	297	4348
12.88	3988.08	296	4353
12.93	3988.08	295	4356
12.98	4002.73	297	4361
13.02	4002.73	296	4366
13.07	4002.73	295	4368
13.12	4002.73	294	4371
13.15	3995.41	291	4373
13.2	3995.41	291	4378
13.25	4017.38	294	4380
13.28	3995.41	288	4385
13.33	4002.73	289	4388
13.37	3988.08	285	4390
13.42	3944.13	276	4395
13.47	3995.41	286	4393
13.5	4010.06	287	4400
13.55	4002.73	284	4408
13.58	4002.73	283	4410
13.63	3995.41	281	4410
13.68	3980.76	277	4415
13.72	4010.06	283	4415
13.77	4010.06	281	4420
13.82	4017.38	282	4425
13.85	4002.73	277	4425
13.9	3995.41	276	4425
13.93	4002.73	276	4432
13.98	4002.73	275	4430
14.03	4010.06	276	4440

14.07	4010.06	275	4442
14.12	3988.08	270	4445
14.17	3980.76	268	4447
14.2	4002.73	272	4452
14.25	4002.73	270	4454
14.3	4017.38	272	4462
14.33	4046.69	277	4462
14.38	3995.41	266	4464
14.42	3995.41	265	4464
14.47	3995.41	265	4462
14.52	4010.06	267	4472
14.55	3995.41	263	4477
14.6	3980.76	259	4477
14.65	3995.41	262	4477
14.68	3995.41	261	4484
14.73	3980.76	257	4489
14.77	4002.73	261	4491
14.82	4010.06	262	4496
14.87	4010.06	261	4499
14.9	4002.73	258	4506
14.95	4024.71	262	4506
15	4010.06	258	4509
15.03	3995.41	254	4509
15.08	4002.73	256	4514
15.12	4017.38	258	4516
15.17	3995.41	252	4516
15.22	3995.41	252	4524
15.25	3995.41	251	4528
15.3	4010.06	254	4528
15.35	4002.73	251	4533
15.38	4017.38	253	4536
15.43	3995.41	248	4538
15.47	3980.76	244	4541
15.52	3958.78	240	4546
15.57	4002.73	249	4548
15.6	4002.73	247	4553
15.65	4017.38	250	4558
15.7	4010.06	247	4561
15.73	3966.1	237	4563
15.78	4002.73	245	4563
15.83	4010.06	245	4570
15.87	3995.41	241	4573
15.92	4002.73	243	4573
15.97	4010.06	243	4575
16	4010.06	243	4580
16.05	4010.06	242	4583
16.1	4010.06	241	4588
16.13	4002.73	239	4590
16.18	3995.41	237	4593
16.22	3973.43	232	4598
16.27	3988.08	235	4600
16.32	4017.38	240	4605
16.35	4010.06	237	4607
16.4	4017.38	239	4610

16.45	4017.38	238	4617
16.48	4002.73	234	4615
16.53	3980.76	229	4615
16.58	3980.76	229	4620
16.62	3988.08	230	4625
16.67	4002.73	232	4625
16.72	4002.73	232	4630
16.75	3995.41	229	4622
16.8	3995.41	229	4637
16.85	4017.38	233	4642
16.88	4010.06	230	4644
16.93	3988.08	225	4644
16.97	4010.06	230	4649
17.02	4017.38	231	4652
17.07	4010.06	228	4659
17.1	4010.06	228	4659
17.15	4002.73	226	4662
17.2	4024.71	230	4664
17.23	4024.71	229	4669
17.28	4024.71	228	4672
17.33	4010.06	224	4677
17.37	4010.06	224	4677
17.42	4010.06	224	4679
17.47	4017.38	224	4684
17.5	3995.41	219	4686
17.55	4002.73	221	4689
17.6	4002.73	220	4694
17.63	4010.06	221	4696
17.68	4010.06	220	4696
17.72	3995.41	217	4696
17.77	3995.41	217	4699
17.82	4002.73	218	4706
17.85	3988.08	214	4704
17.9	3995.41	215	4711
17.95	4002.73	216	4714
17.98	3966.1	207	4716
18.03	4002.73	216	4716
18.08	3988.08	212	4726
18.12	3988.08	211	4723
18.17	3988.08	211	4726
18.22	4002.73	214	4726
18.25	3988.08	210	4736
18.3	3988.08	210	4736
18.35	4010.06	214	4738
18.38	4017.38	214	4733
18.43	4010.06	212	4746
18.47	4010.06	212	4746
18.52	4010.06	211	4751
18.57	4002.73	209	4746
18.6	3995.41	207	4758
18.65	4017.38	212	4761
18.7	4024.71	212	4753
18.73	4039.36	215	4765
18.78	4032.04	213	4768

18.83	4024.71	210	4770
18.87	4024.71	210	4775
18.92	4032.04	211	4775
18.97	4039.36	212	4778
19	4017.38	206	4780
19.05	4010.06	205	4780
19.08	4002.73	203	4780
19.13	3995.41	201	4785
19.18	4010.06	204	4788
19.22	4010.06	203	4790
19.27	4002.73	201	4795
19.32	4024.71	206	4795
19.35	4010.06	202	4798
19.4	4017.38	203	4800
19.45	4010.06	201	4810
19.48	4010.06	201	4805
19.53	4017.38	202	4807
19.58	4010.06	200	4810
19.62	4010.06	199	4812
19.67	4010.06	199	4815
19.72	4024.71	202	4820
19.75	4010.06	198	4822
19.8	4024.71	201	4822
19.83	4039.36	203	4827
19.88	4039.36	203	4827
19.93	4054.01	205	4832
19.97	4046.69	203	4835
20.02	4039.36	201	4835
20.07	4039.36	200	4835
20.1	4024.71	196	4837
20.15	4039.36	200	4842
20.2	4024.71	196	4844
20.23	4032.04	197	4844
20.28	4046.69	200	4849
20.33	4010.06	191	4849
20.37	4024.71	194	4852
20.42	4024.71	194	4854
20.47	4010.06	190	4849
20.5	4010.06	190	4857
20.55	4024.71	193	4859
20.58	4039.36	196	4862
20.63	4039.36	195	4864
20.68	4046.69	196	4867
20.72	4075.99	202	4867
20.77	3988.08	181	4869
20.82	3973.43	179	4869
20.85	3966.1	178	4867
20.9	3988.08	183	4869
20.93	3980.76	180	4872
20.98	3980.76	180	4879
21.03	4010.06	186	4879
21.07	3980.76	179	4879
21.12	3995.41	183	4894
21.17	3966.1	176	4881

21.2	3966.1	176	4889
21.25	3944.13	171	4889
21.28	3980.76	180	4889
21.33	3995.41	182	4891
21.38	4002.73	183	4899
21.42	3988.08	179	4901
21.47	3973.43	176	4896
21.52	3973.43	176	4906
21.55	3966.1	174	4906
21.6	3995.41	180	4906
21.65	3980.76	176	4906
21.68	3988.08	178	4914
21.73	3980.76	176	4914
21.78	4024.71	185	4918
21.82	4010.06	181	4921
21.87	4024.71	184	4923
21.9	4002.73	178	4923
21.95	4010.06	180	4926
22	4010.06	180	4931
22.03	4010.06	179	4933
22.08	4017.38	180	4933
22.13	4010.06	178	4936
22.17	3995.41	175	4936
22.22	4017.38	180	4938
22.25	4002.73	175	4941
22.3	4010.06	177	4941
22.35	4024.71	180	4946
22.38	4010.06	176	4948
22.43	4010.06	176	4948
22.48	3980.76	169	4951
22.52	3995.41	173	4951
22.57	3980.76	169	4955
22.62	3995.41	172	4958
22.65	4010.06	175	4960
22.7	4010.06	174	4960
22.75	3995.41	171	4963
22.78	3995.41	170	4963
22.83	4024.71	177	4965
22.87	4002.73	171	4968
22.92	4010.06	173	4970
22.97	3980.76	166	4973
23	3995.41	169	4973
23.05	4002.73	170	4978
23.1	4002.73	170	4978
23.13	3966.1	161	4983
23.18	4002.73	170	4983
23.22	3995.41	167	4985
23.27	3995.41	167	4990
23.32	4032.04	175	4990
23.35	3995.41	166	4993
23.4	3988.08	165	4983
23.45	3995.41	166	4997
23.48	3980.76	162	4990
23.53	3988.08	164	5000

23.58	3995.41	165	5015
23.62	4002.73	167	5005
23.67	3988.08	163	5005
23.7	3980.76	161	5007
23.75	3995.41	165	5012
23.8	3980.76	161	5015
23.83	3988.08	162	5015
23.88	3995.41	164	5017
23.93	3980.76	160	5020
23.97	3995.41	163	5022
24.02	3995.41	163	5025
24.07	3988.08	161	5030
24.1	4002.73	164	5032
24.15	4010.06	165	5037
24.18	4002.73	163	5034
24.23	4002.73	163	5049
24.28	4017.38	166	5042
24.32	3988.08	158	5039
24.37	4002.73	162	5047
24.42	4002.73	162	5047
24.45	4002.73	161	5049
24.5	3995.41	159	5049
24.55	4002.73	161	5054
24.58	3988.08	157	5057
24.63	3995.41	159	5057
24.68	3951.45	148	5059
24.72	3980.76	156	5062
24.77	3973.43	153	5062
24.8	3988.08	157	5067
24.85	3995.41	158	5067
24.9	3988.08	156	5079
24.93	3995.41	157	5076
24.98	3995.41	157	5074
25.03	3995.41	157	5079
25.07	4039.36	167	5081
25.12	4010.06	159	5086
25.17	3995.41	155	5084
25.2	3980.76	152	5086
25.25	4010.06	159	5086
25.28	3995.41	154	5081
25.33	3980.76	151	5091
25.38	4002.73	156	5096
25.42	3980.76	150	5096
25.47	4002.73	156	5101
25.5	4010.06	157	5101
25.55	3995.41	153	5106
25.6	3973.43	148	5109
25.63	3973.43	148	5111
25.68	4010.06	156	5113
25.73	4010.06	156	5116
25.77	4002.73	153	5104
25.82	4010.06	155	5118
25.87	4002.73	153	5123
25.9	4010.06	154	5126

25.95	3973.43	146	5128
26	4002.73	153	5131
26.03	3995.41	150	5133
26.08	4010.06	154	5136
26.13	4032.04	158	5136
26.17	4010.06	152	5141
26.22	4032.04	157	5146
26.25	4010.06	152	5143
26.3	4010.06	152	5146
26.35	4017.38	153	5150
26.38	4010.06	151	5153
26.43	4002.73	149	5153
26.48	3995.41	147	5155
26.52	4002.73	149	5158
26.57	4010.06	150	5160
26.62	4032.04	155	5163
26.65	4017.38	151	5165
26.7	3988.08	144	5168
26.73	4002.73	148	5163
26.78	3995.41	146	5175
26.83	4039.36	156	5173
26.87	4024.71	151	5178
26.92	4024.71	151	5178
26.97	4002.73	146	5180
27	4017.38	149	5180
27.05	4002.73	145	5180
27.1	4010.06	147	5183
27.13	4002.73	145	5190
27.18	4002.73	145	5187
27.22	3995.41	143	5187
27.27	4002.73	145	5187
27.32	3995.41	143	5192
27.35	4017.38	148	5197
27.4	4024.71	149	5200
27.45	3995.41	141	5200
27.48	3995.41	142	5202
27.53	3995.41	142	5205
27.58	4039.36	151	5202
27.62	3980.76	136	5207
27.67	3973.43	136	5207
27.7	3973.43	136	5205
27.75	3966.1	134	5210
27.8	3958.78	132	5210
27.85	3973.43	136	5215
27.88	3958.78	132	5220
27.93	3958.78	132	5220
27.97	3966.1	134	5225
28.02	3944.13	129	5227
28.07	3973.43	136	5227
28.1	3980.76	137	5234
28.15	3995.41	140	5234
28.2	4024.71	146	5234
28.23	3973.43	133	5237
28.28	3973.43	134	5239

28.32	3951.45	129	5242
28.37	3980.76	136	5259
28.42	3973.43	134	5249
28.45	3966.1	132	5252
28.5	4002.73	141	5254
28.55	3995.41	138	5259
28.58	3966.1	131	5259
28.63	3988.08	137	5259
28.67	3988.08	136	5262
28.72	3980.76	134	5274
28.77	4010.06	141	5269
28.8	4017.38	142	5259
28.85	4002.73	138	5274
28.9	3995.41	136	5276
28.93	4024.71	143	5276
28.98	4002.73	137	5284
29.03	4024.71	142	5284
29.07	4024.71	141	5286
29.12	4032.04	143	5281
29.17	4010.06	137	5291
29.2	4032.04	143	5294
29.25	4046.69	145	5299
29.28	4032.04	141	5301
29.33	4039.36	143	5301
29.38	4046.69	144	5303
29.42	4046.69	143	5306
29.47	4046.69	143	5308
29.52	4039.36	141	5313
29.55	4024.71	137	5311
29.6	4024.71	137	5316
29.65	4010.06	134	5318
29.68	4032.04	139	5316
29.73	4010.06	133	5321
29.78	4032.04	138	5321
29.82	4061.34	145	5321
29.87	4017.38	134	5326
29.9	4032.04	137	5326
29.95	3980.76	125	5331
30	4017.38	134	5333

Time	DKEST	INVK	INVKAVE	DKBAL	a0	b0	b1
4.00E-02	2.50E-02	2.50E-02	1.25E-02	4.93E-04	0	0	0
9.00E-02	5.00E-02	5.00E-02	3.75E-02	1.33E-02	-3.50E-02	0.572183	1.31E-02
0.13	0.127	0.127	8.85E-02	2.60E-02	-0.14356	1.74877	3.93E-02
0.17	0.149	0.149	0.138	6.09E-02	-0.60418	4.37332	9.73E-02
0.22	-1.60E-02	-1.60E-02	6.65E-02	0.106795	-1.15859	3.16403	8.52E-02
0.25	-1.00E-03	-1.00E-03	-8.50E-03	9.63E-02	-0.16619	12.2872	0.216762
0.3	0.277	0.277	0.138	0.102987	0.74514	21.5962	0.36101
0.33	0.156	0.156	0.2165	0.143796	-1.11433	5.20852	1.00E-01
0.38	0.195	0.195	0.1755	0.145151	-1.27323	3.62486	7.43E-02
0.42	0.1875	0.185	0.19	0.159475	-2.01232	-4.59485	-5.98E-02
0.47	0.153	0.153	0.169	0.180583	-2.48055	-10.3814	-0.15374
0.5	0.204196	0.254	0.2035	0.204892	-1.97056	-3.49128	-4.29E-02
0.53	0.295	0.295	0.2745	0.227804	-1.95662	-3.29244	-3.97E-02
0.58	9.00E-02	9.00E-02	0.1925	0.259552	-3.42615	-24.7509	-0.384
0.63	0.492	0.492	0.291	0.271265	0.621924	36.3554	-0.7288
0.67	0.267	0.267	0.3795	0.313299	-4.83517	-45.8143	-0.4238
0.7	0.306007	0.341	0.304	0.308013	-3.54283	-26.5585	-0.40968
0.75	0.320098	0.296	0.3185	0.321696	-3.48391	-25.6626	-0.39782
0.8	0.2885	0.286	0.291	0.348144	-3.4346	-24.9066	0.588285
0.83	0.543	0.543	0.4145	0.370554	-1.53219	4.65706	6.45E-02
0.87	0.352	0.352	0.4475	0.408052	-7.15336	-82.481	-1.30008
0.92	0.3565	0.358	0.355	0.405491	-5.18245	-52.3171	-0.83434
0.97	0.331	0.331	0.3445	0.412269	-3.42769	-25.1728	-0.41817
1	0.33175	0.332	0.3315	0.432182	-0.49592	20.2034	-0.1234
1.05	0.401	0.401	0.3665	0.452468	3.12144	75.2534	0.145
1.08	0.479988	0.48	0.4405	0.479977	4.97502	102.25	0.276076
1.13	0.5224	0.562	0.521	0.5238	4.97461	102.245	1.12164
1.17	0.539703	0.51	0.536	0.543406	5.028	102.91	1.53976
1.22	0.566956	0.562	0.536	0.571912	5.17883	104.598	1.53967
1.25	0.532	0.522	0.542	0.604375	5.39105	106.766	1.55018
1.3	0.617013	0.605	0.5635	0.629026	8.68555	137.222	1.57704
1.33	0.62825	0.636	0.6205	0.662702	9.26011	142.024	1.61188
1.38	0.684043	0.675	0.6555	0.693087	11.0321	155.131	2.10579
1.42	0.615	0.615	0.645	0.727043	11.5368	158.396	2.18435
1.47	0.698	0.698	0.6565	0.758597	18.4112	196.842	2.40076
1.5	0.695	0.694	0.696	0.791764	22.3959	216.277	2.45511
1.55	0.7075	0.712	0.703	0.825066	29.3867	245.12	3.10061
1.58	0.73	0.736	0.724	0.857507	38.6738	277.304	3.42865
1.63	0.7795	0.794	0.765	0.905712	49.7018	308.898	3.91698
1.68	0.82325	0.833	0.8135	0.917892	61.704	336.756	4.46101
1.72	0.80525	0.796	0.8145	0.937387	71.8614	355.049	4.99036
1.77	0.835	0.848	0.822	0.945626	88.2551	377.077	5.44833
1.8	0.8405	0.838	0.843	0.953313	103.599	392.649	5.73948
1.85	0.85525	0.861	0.8495	0.958749	121.475	405.71	6.07377
1.88	0.822	0.809	0.835	0.961919	139.947	415.237	6.293
1.93	0.83075	0.838	0.8235	0.966053	168.288	424.963	6.45636
1.98	0.856	0.862	0.85	0.975096	198.146	431.506	6.55331
2.02	0.847	0.842	0.852	0.976713	226.868	434.862	6.61625
2.07	0.86525	0.873	0.8575	0.981717	261.566	435.993	6.61431
2.1	0.873	0.873	0.873	0.983909	295.542	434.846	6.55955

2.15	0.898147	0.849	0.861	0.984439	331.36	431.717	6.44423
2.18	0.87075	0.878	0.8635	0.976488	362.081	427.717	6.2921
2.23	0.851	0.842	0.86	0.955143	402.616	420.964	6.10125
2.27	0.85925	0.865	0.8535	0.971489	446.029	412.446	5.91658
2.32	0.86575	0.866	0.8655	0.963366	495.607	401.251	5.64581
2.35	0.863	0.862	0.864	0.945989	541.52	389.682	5.33293
2.4	0.883674	0.849	0.8555	0.946522	583.011	378.224	4.9418
2.45	0.85125	0.852	0.8505	0.941143	616.105	368.29	4.54971
2.48	0.86025	0.863	0.8575	0.927359	665.148	352.298	4.16719
2.53	0.882776	0.865	0.864	0.919327	702.839	338.984	3.83605
2.58	0.832	0.821	0.843	0.911764	723.914	330.996	3.29779
2.62	0.83525	0.84	0.8305	0.895574	770.814	312.101	2.84057
2.67	0.851449	0.831	0.8355	0.887846	805.829	296.628	2.55864
2.7	0.840655	0.82	0.8255	0.876465	826.589	286.63	1.87013
2.75	0.85356	0.854	0.837	0.869679	846.387	276.222	1.27849
2.8	0.859532	0.857	0.8555	0.866096	854.892	271.315	0.875542
2.83	0.846846	0.839	0.848	0.853537	858.22	269.267	0.432179
2.88	0.846056	0.85	0.8445	0.843669	861.464	267.163	0.210478
2.92	0.84323	0.857	0.8535	0.819189	860.38	267.915	0.112537
2.97	0.833558	0.835	0.846	0.819673	850.191	275.394	0.48079
3.02	0.83833	0.859	0.847	0.808991	844.704	279.586	0.741548
3.05	0.794522	0.786	0.8225	0.803044	834.137	288.2	1.31786
3.1	0.801582	0.833	0.8095	0.793664	836.991	285.828	1.14686
3.13	0.816252	0.832	0.8325	0.784257	834.679	288.001	1.31649
3.18	0.821298	0.847	0.8395	0.777394	826.342	296.475	2.03415
3.23	0.8425	0.841	0.844	0.772616	816.063	307.574	3.05365
3.27	0.82705	0.859	0.85	0.772151	800.855	323.992	4.69904
3.32	0.856	0.855	0.857	0.763757	789.609	335.806	5.99381
3.35	0.86025	0.862	0.8585	0.765347	770.957	353.317	8.13613
3.4	0.8395	0.832	0.847	0.753566	751.588	368.726	10.2784
3.45	0.817135	0.857	0.8445	0.749903	733.346	380.021	12.1321
3.48	0.84275	0.838	0.8475	0.74042	719.38	387.531	13.5692
3.53	0.84775	0.851	0.8445	0.738611	697.095	395.986	15.6693
3.57	0.83825	0.834	0.8425	0.733298	672.785	402.416	17.8541
3.62	0.81225	0.805	0.8195	0.720564	648.022	405.534	19.8427
3.67	0.788443	0.831	0.818	0.716329	625.813	406.194	21.5249
3.7	0.807693	0.854	0.8425	0.726578	609.016	406.121	22.8846
3.75	0.83375	0.827	0.8405	0.714094	589.707	404.491	24.3781
3.78	0.85775	0.868	0.8475	0.713435	558.589	398.153	26.3903
3.83	0.85375	0.849	0.8585	0.7076	519.708	387.42	28.7159
3.88	0.84675	0.846	0.8475	0.704711	475.044	369.893	30.5846
3.92	0.843	0.842	0.844	0.700881	427.86	347.501	31.98
3.97	0.84575	0.847	0.8445	0.704417	377.503	320.198	32.9268
4	0.823	0.815	0.831	0.707322	325.005	288.719	33.3838
4.05	0.798422	0.848	0.8315	0.715767	280.128	259.354	33.2614
4.1	0.84725	0.847	0.8475	0.708246	248.404	237.452	32.954
4.13	0.83125	0.826	0.8365	0.72458	194.15	197.459	31.8061
4.18	0.80298	0.837	0.8315	0.74044	151.873	164.275	30.3221
4.23	0.812611	0.853	0.845	0.739834	127.685	144.361	29.1818
4.27	0.8515	0.851	0.852	0.751929	100.448	120.869	27.547
4.32	0.8435	0.841	0.846	0.764941	64.1218	87.8862	24.7879

4.37	0.8305	0.827	0.834	0.779848	36.6339	61.6789	22.2224
4.4	0.816644	0.833	0.83	0.786932	20.1083	45.229	20.3954
4.45	0.82291	0.835	0.834	0.799729	11.2726	36.0905	19.2705
4.5	0.824408	0.831	0.833	0.809224	5.00409	29.3475	18.3608
4.53	0.837516	0.854	0.8425	0.816047	1.2767	25.1738	17.7499
4.58	0.836827	0.834	0.844	0.832479	-3.48489	19.6273	16.879
4.63	0.831341	0.832	0.833	0.829023	-4.36669	18.5528	16.6988
4.67	0.83831	0.841	0.8365	0.837431	-4.78974	18.016	16.6038
4.72	0.836497	0.833	0.837	0.839489	-4.93395	17.8256	16.5685
4.77	0.840386	0.837	0.835	0.849158	-4.49049	18.4363	16.6864
4.8	0.836919	0.829	0.833	0.848758	-3.32025	20.1142	17.0215
4.85	0.83813	0.835	0.832	0.847391	-1.89195	22.2489	17.4597
4.9	0.838134	0.832	0.8335	0.848901	-0.88437	23.8157	17.7884
4.93	0.838363	0.832	0.832	0.851088	0.17739	25.535	18.155
4.98	0.837954	0.831	0.8315	0.851363	1.31713	27.4568	18.5691
5.03	0.835647	0.826	0.8285	0.852441	2.41	29.3752	18.9847
5.07	0.827878	0.817	0.8215	0.845132	3.65703	31.6527	19.4781
5.12	0.82304	0.813	0.815	0.841119	4.82479	33.8691	19.9557
5.17	0.815077	0.803	0.808	0.83423	5.9388	36.0623	20.4237
5.2	0.803524	0.793	0.798	0.819571	7.01418	38.2549	20.8845
5.25	0.797887	0.788	0.7905	0.815161	7.83546	39.9858	21.2409
5.28	0.789336	0.779	0.7835	0.805507	8.64247	41.741	21.5929
5.33	0.785602	0.776	0.7775	0.803307	9.33365	43.2901	21.8933
5.38	0.777349	0.772	0.774	0.786045	10.0278	44.8912	22.1908
5.42	0.776543	0.766	0.769	0.794629	10.3416	45.6356	22.3219
5.47	0.771801	0.762	0.764	0.789402	10.9453	47.108	22.5645
5.5	0.764068	0.753	0.7575	0.781703	11.4902	48.4733	22.7711
5.55	0.759308	0.75	0.7515	0.776425	11.9979	49.7793	22.9483
5.58	0.749512	0.739	0.7445	0.765036	12.4568	50.9894	23.0904
5.63	0.744001	0.735	0.737	0.760003	12.8453	52.0389	23.1916
5.68	0.738132	0.728	0.7315	0.754897	13.2196	53.0731	23.2668
5.72	0.73273	0.723	0.7255	0.74969	13.5869	54.1102	23.3141
5.77	0.72492	0.715	0.719	0.740761	13.9356	55.1156	23.3291
5.8	0.71958	0.712	0.7135	0.73324	14.2419	56.0169	23.3113
5.85	0.712958	0.703	0.7075	0.728375	14.4906	56.7627	23.2675
5.88	0.703264	0.694	0.6985	0.717293	14.7555	57.5723	23.1849
5.93	0.698999	0.69	0.692	0.714996	14.9831	58.2801	23.0783
5.98	0.693201	0.683	0.6865	0.710104	15.2283	59.0554	22.9195
6.02	0.684851	0.676	0.6795	0.699052	15.4734	59.8426	22.7106
6.07	0.681185	0.67	0.673	0.700554	15.6684	60.4785	22.499
6.1	0.672476	0.662	0.666	0.689427	15.9206	61.313	22.1591
6.15	0.667568	0.658	0.66	0.684704	16.13	62.0152	21.8145
6.2	0.658305	0.648	0.653	0.673914	16.331	62.698	21.4161
6.23	0.651347	0.642	0.645	0.667041	16.5049	63.2962	21.0057
6.28	0.643666	0.634	0.638	0.658997	16.6709	63.8741	20.5431
6.33	0.63843	0.629	0.6315	0.654789	16.8251	64.4167	20.0405
6.37	0.630373	0.619	0.624	0.64812	16.9814	64.9724	19.4477
6.42	0.623085	0.613	0.616	0.640255	17.1426	65.551	18.7411
6.45	0.619464	0.608	0.6105	0.639893	17.2907	66.0876	17.9932
6.5	0.617054	0.606	0.607	0.638161	17.4581	66.6987	17.0238
6.55	0.614014	0.605	0.6055	0.631541	17.6222	67.3033	15.9369

6.58	0.609344	0.597	0.601	0.630032	17.7517	67.784	14.961
6.63	0.602847	0.591	0.594	0.623541	17.897	68.3284	13.7202
6.67	0.598534	0.587	0.589	0.619601	18.0351	68.8499	12.3867
6.72	0.595884	0.584	0.5855	0.618152	18.1684	69.3575	10.9314
6.77	0.590767	0.579	0.5815	0.611801	18.302	69.8701	9.28672
6.8	0.586991	0.574	0.5765	0.610471	18.4215	70.3323	7.62932
6.85	0.584881	0.574	0.574	0.606643	18.5477	70.8243	5.65982
6.88	0.579138	0.565	0.5695	0.602913	18.6582	71.2584	3.7205
6.93	0.571358	0.559	0.562	0.593074	18.7721	71.7099	1.4745
6.97	0.565871	0.554	0.5565	0.587112	18.8699	72.101	-0.69711
7.02	0.565754	0.552	0.553	0.592261	18.9595	72.4623	-2.94225
7.07	0.564944	0.551	0.5515	0.592332	19.0639	72.8868	-5.8982
7.1	0.563884	0.55	0.5505	0.591151	19.1643	73.2988	-9.11527
7.15	0.561235	0.545	0.5475	0.591206	19.2571	73.6835	-12.4829
7.18	0.558179	0.543	0.544	0.587537	19.3515	74.0795	-16.3681
7.23	0.54375	0.544	0.5435	0.598621	19.4364	74.441	-20.3581
7.28	0.55531	0.539	0.5415	0.585431	19.5816	75.0682	-28.1653
7.32	0.551267	0.535	0.537	0.5818	19.654	75.3867	-32.6479
7.37	0.535	0.535	0.535	0.58064	19.72	75.6837	-37.3954
7.4	0.546045	0.527	0.531	0.580134	19.8077	76.0888	-44.8
7.45	0.540263	0.523	0.525	0.572789	19.8653	76.3632	-50.5643
7.5	0.52375	0.524	0.5235	0.572906	19.9124	76.5969	-56.2917
7.53	0.52025	0.519	0.5215	0.574836	19.9716	76.9066	-65.2946
7.58	0.51825	0.518	0.5185	0.57291	20.0245	77.204	-75.6801
7.63	0.532024	0.514	0.516	0.566071	20.0644	77.455	-86.4748
7.67	0.511	0.51	0.512	0.56487	20.0813	77.5823	-93.4483
7.72	0.5115	0.512	0.511	0.566638	20.0952	77.7377	-104.877
7.75	0.524221	0.503	0.5075	0.562163	20.0964	77.8495	-116.98
7.8	0.503	0.503	0.503	0.570612	20.0885	77.8952	-125.588
7.83	0.4985	0.497	0.5	0.562009	20.0583	77.9176	-141.426
7.88	0.494	0.493	0.495	0.560883	20.0149	77.8841	-156.771
7.93	0.49075	0.49	0.4915	0.552248	19.9532	77.7899	-173.428
7.97	0.48775	0.487	0.4885	0.544969	19.8815	77.6478	-189.202
8.02	0.48475	0.484	0.4855	0.540226	19.8009	77.4641	-204.301
8.07	0.48175	0.481	0.4825	0.537935	19.7093	77.2363	-219.343
8.1	0.48025	0.48	0.4805	0.536752	19.6031	76.9554	-234.976
8.15	0.4785	0.478	0.479	0.52808	19.4828	76.6228	-251.085
8.18	0.47425	0.473	0.4755	0.533065	19.3658	76.2888	-265.55
8.23	0.47375	0.474	0.4735	0.527759	19.2137	75.8435	-283.079
8.28	0.486035	0.469	0.4715	0.517604	19.0619	75.3898	-299.502
8.32	0.46675	0.466	0.4675	0.52061	18.9664	75.0997	-309.28
8.37	0.4675	0.468	0.467	0.518811	18.7922	74.5634	-326.24
8.4	0.476548	0.459	0.4635	0.507144	18.6159	74.0146	-342.639
8.45	0.45675	0.456	0.4575	0.511128	18.505	73.6664	-352.547
8.48	0.45225	0.451	0.4535	0.50523	18.2977	73.01	-370.358
8.53	0.45025	0.45	0.4505	0.509048	18.0862	72.3353	-387.879
8.58	0.45	0.45	0.45	0.496431	17.8413	71.5486	-407.484
8.62	0.461779	0.445	0.4475	0.492837	17.6404	70.8994	-423.07
8.67	0.4495	0.451	0.448	0.491191	17.5014	70.4483	-433.549
8.7	0.455844	0.438	0.4445	0.485033	17.309	69.8221	-447.659
8.75	0.44325	0.445	0.4415	0.485689	17.171	69.3723	-457.549

8.8	0.453206	0.437	0.441	0.481618	16.9656	68.7011	-471.918
8.83	0.448197	0.431	0.434	0.479589	16.8256	68.2435	-481.514
8.88	0.4325	0.433	0.432	0.476037	16.6684	67.7293	-492.072
8.93	0.4345	0.435	0.434	0.466476	16.4473	67.006	-506.624
8.97	0.440988	0.427	0.431	0.464965	16.2832	66.4693	-517.231
9.02	0.42775	0.428	0.4275	0.462657	16.1593	66.065	-525.115
9.05	0.435049	0.422	0.425	0.458146	15.9779	65.4742	-536.47
9.1	0.432787	0.422	0.422	0.454361	15.8576	65.0836	-543.895
9.13	0.428933	0.416	0.419	0.451799	15.7452	64.7195	-550.737
9.18	0.425763	0.416	0.416	0.44529	15.6263	64.3358	-557.882
9.23	0.425382	0.417	0.4165	0.442646	15.5252	64.0106	-563.884
9.27	0.424843	0.414	0.4155	0.445029	15.4363	63.7261	-569.099
9.32	0.423104	0.416	0.415	0.438311	15.3333	63.3985	-575.085
9.35	0.416781	0.407	0.4115	0.431842	15.2565	63.156	-579.509
9.4	0.414859	0.408	0.4075	0.429078	15.1815	62.921	-583.802
9.45	0.412672	0.406	0.407	0.425015	15.1117	62.7039	-587.772
9.48	0.411418	0.406	0.406	0.422255	15.052	62.5201	-591.144
9.53	0.409084	0.404	0.405	0.418253	15.0005	62.3632	-594.039
9.58	0.4031	0.397	0.4005	0.4118	14.9577	62.2345	-596.435
9.62	0.399529	0.394	0.3955	0.409087	14.918	62.1164	-598.657
9.67	0.39349	0.394	0.394	0.392471	14.8752	61.991	-601.042
9.7	0.396558	0.394	0.394	0.401674	14.8797	62.0039	-600.793
9.75	0.394506	0.39	0.392	0.401519	14.8578	61.9417	-602.011
9.78	0.38938	0.383	0.3865	0.398639	14.8286	61.8601	-603.642
9.83	0.388921	0.389	0.386	0.391763	14.791	61.7572	-605.746
9.88	0.388268	0.39	0.3895	0.385305	14.7797	61.727	-606.377
9.92	0.388335	0.388	0.389	0.388004	14.7911	61.7569	-605.734
9.97	0.388972	0.39	0.389	0.387915	14.7924	61.76	-605.664
10	0.387432	0.388	0.389	0.385295	14.7962	61.7694	-605.444
10.05	0.383818	0.384	0.386	0.381454	14.8037	61.7871	-605.008
10.1	0.384279	0.388	0.386	0.378838	14.8117	61.8053	-604.535
10.13	0.38021	0.381	0.3845	0.375129	14.8295	61.8438	-603.467
10.18	0.375953	0.379	0.38	0.36886	14.8456	61.8766	-602.487
10.23	0.372823	0.375	0.377	0.366468	14.8672	61.9181	-601.142
10.27	0.368576	0.372	0.3735	0.360227	14.8859	61.9514	-599.957
10.32	0.363287	0.369	0.3705	0.350362	14.9095	61.9902	-598.424
10.35	0.365033	0.369	0.369	0.357099	14.9448	62.0428	-596.087
10.4	0.361036	0.361	0.365	0.357107	14.9655	62.0705	-594.674
10.45	0.361587	0.365	0.363	0.356761	14.9754	62.082	-593.983
10.48	0.359294	0.366	0.3655	0.346381	14.9871	62.0933	-593.146
10.53	0.358034	0.363	0.3645	0.346603	15.017	62.1162	-590.932
10.57	0.35572	0.361	0.362	0.34416	15.0422	62.1295	-588.991
10.62	0.3565	0.355	0.358	0.337925	15.0666	62.1361	-587.047
10.67	0.349506	0.355	0.355	0.338517	15.1039	62.1357	-583.948
10.7	0.350225	0.359	0.357	0.334676	15.125	62.1292	-582.13
10.75	0.349457	0.356	0.3575	0.33487	15.1532	62.111	-579.576
10.8	0.3545	0.354	0.355	0.322445	15.1783	62.0852	-577.193
10.83	0.345225	0.354	0.354	0.327676	15.2302	62.0091	-571.979
10.88	0.3525	0.352	0.353	0.327941	15.257	61.9571	-569.137
10.92	0.35125	0.351	0.3515	0.32499	15.2921	61.8697	-565.173
10.97	0.34575	0.344	0.3475	0.319654	15.3271	61.7607	-560.945

11.02	0.33769	0.347	0.3455	0.320571	15.3595	61.6371	-556.753
11.05	0.34775	0.348	0.3475	0.305703	15.3792	61.5464	-554.009
11.1	0.34575	0.345	0.3465	0.319041	15.4237	61.2993	-547.277
11.15	0.339472	0.344	0.3445	0.329916	15.4496	61.1269	-543.002
11.18	0.34325	0.343	0.3435	0.313135	15.458	61.0598	-541.473
11.23	0.34375	0.344	0.3435	0.311671	15.4817	60.8309	-536.65
11.27	0.341	0.34	0.342	0.312836	15.5042	60.5685	-531.504
11.32	0.3385	0.338	0.339	0.303687	15.5214	60.3219	-526.976
11.37	0.338	0.338	0.338	0.3088	15.5396	59.9972	-521.367
11.4	0.3365	0.336	0.337	0.305954	15.5524	59.7087	-516.652
11.45	0.33525	0.335	0.3355	0.304441	15.5632	59.3899	-511.706
11.5	0.327393	0.342	0.3385	0.30168	15.5715	59.0513	-506.701
11.53	0.33675	0.335	0.3385	0.295945	15.5762	58.7547	-502.509
11.58	0.332	0.331	0.333	0.297627	15.5802	58.26	-495.824
11.62	0.33025	0.33	0.3305	0.298848	15.5807	57.8242	-490.168
11.67	0.33075	0.331	0.3305	0.28733	15.5787	57.4095	-484.98
11.72	0.321982	0.335	0.333	0.297946	15.5723	56.8134	-477.778
11.75	0.329	0.327	0.331	0.280805	15.5669	56.4708	-473.774
11.8	0.33075	0.332	0.3295	0.288004	15.5521	55.7574	-465.7
11.85	0.326	0.324	0.328	0.293525	15.5357	55.1028	-458.508
11.88	0.3255	0.326	0.325	0.288328	15.5206	54.5887	-453.017
11.93	0.32225	0.321	0.3235	0.295952	15.5006	53.9822	-446.706
11.97	0.32025	0.32	0.3205	0.290278	15.4845	53.5403	-442.221
12.02	0.310783	0.325	0.3225	0.28485	15.464	53.0225	-437.088
12.07	0.32125	0.32	0.3225	0.284065	15.4443	52.5621	-432.626
12.1	0.317	0.316	0.318	0.279104	15.4133	51.8835	-426.193
12.15	0.3145	0.314	0.315	0.280521	15.379	51.1738	-419.604
12.18	0.31475	0.315	0.3145	0.279268	15.3458	50.5219	-413.669
12.23	0.30975	0.308	0.3115	0.276805	15.3087	49.8256	-407.445
12.28	0.302035	0.316	0.312	0.278105	15.2721	49.1645	-401.64
12.32	0.313	0.312	0.314	0.276071	15.2439	48.6745	-397.409
12.37	0.31125	0.311	0.3115	0.27105	15.1979	47.9018	-390.847
12.42	0.3095	0.309	0.31	0.272795	15.145	47.0432	-383.671
12.45	0.306	0.305	0.307	0.274305	15.0944	46.2438	-377.091
12.5	0.30425	0.304	0.3045	0.268949	15.0486	45.5408	-371.387
12.55	0.30025	0.299	0.3015	0.27037	14.9954	44.7442	-365.013
12.58	0.291005	0.304	0.3015	0.267514	14.9486	44.0588	-359.6
12.63	0.30175	0.301	0.3025	0.270676	14.9104	43.5117	-355.333
12.67	0.2995	0.299	0.3	0.262622	14.8581	42.7763	-349.669
12.72	0.291049	0.302	0.3005	0.270646	14.7937	41.8902	-342.926
12.77	0.30125	0.301	0.3015	0.257896	14.757	41.3929	-339.185
12.8	0.2995	0.299	0.3	0.262418	14.6762	40.3206	-331.209
12.85	0.2975	0.297	0.298	0.257382	14.6051	39.3906	-324.368
12.88	0.29625	0.296	0.2965	0.259108	14.5258	38.3712	-316.948
12.93	0.29525	0.295	0.2955	0.25803	14.4505	37.4161	-310.065
12.98	0.2965	0.297	0.296	0.259581	14.3731	36.4481	-303.158
13.02	0.29625	0.296	0.2965	0.261106	14.2944	35.4777	-296.298
13.07	0.29525	0.295	0.2955	0.258604	14.2177	34.5444	-289.761
13.12	0.29425	0.294	0.2945	0.257524	14.136	33.5615	-282.938
13.15	0.29175	0.291	0.2925	0.255159	14.0524	32.5674	-276.098
13.2	0.291	0.291	0.291	0.256724	13.9674	31.5686	-269.282

13.25	0.29325	0.294	0.2925	0.254227	13.8864	30.6257	-262.9
13.28	0.2895	0.288	0.291	0.255965	13.7924	29.5444	-255.639
13.33	0.28875	0.289	0.2885	0.254757	13.7103	28.6086	-249.403
13.37	0.286	0.285	0.287	0.252279	13.6258	27.6542	-243.091
13.42	0.27825	0.276	0.2805	0.253727	13.5407	26.7019	-236.838
13.47	0.270819	0.286	0.281	0.245457	13.4779	26.006	-232.301
13.5	0.28675	0.287	0.2865	0.248929	13.4123	25.2838	-227.623
13.55	0.28475	0.284	0.2855	0.254556	13.3131	24.2017	-220.661
13.58	0.28325	0.283	0.2835	0.251856	13.2329	23.3339	-215.116
13.63	0.2815	0.281	0.282	0.246639	13.1485	22.4281	-209.365
13.68	0.278	0.277	0.279	0.24821	13.0538	21.4188	-202.997
13.72	0.268647	0.283	0.28	0.24294	12.972	20.5538	-197.574
13.77	0.2815	0.281	0.282	0.243891	12.9008	19.806	-192.912
13.82	0.28175	0.282	0.2815	0.245671	12.7956	18.7092	-186.117
13.85	0.27825	0.277	0.2795	0.240842	12.6938	17.655	-179.623
13.9	0.27625	0.276	0.2765	0.236148	12.5874	16.5603	-172.919
13.93	0.276	0.276	0.276	0.240812	12.4725	15.386	-165.766
13.98	0.27525	0.275	0.2755	0.233422	12.3711	14.3556	-159.524
14.03	0.27575	0.276	0.2755	0.242176	12.2499	13.1314	-152.146
14.07	0.27525	0.275	0.2755	0.239958	12.1521	12.1496	-146.26
14.12	0.27125	0.27	0.2725	0.239187	12.0488	11.1188	-140.112
14.17	0.2685	0.268	0.269	0.236942	11.9546	10.1839	-134.563
14.2	0.260202	0.272	0.27	0.238606	11.8616	9.26578	-129.14
14.25	0.2705	0.27	0.271	0.235683	11.7978	8.63929	-125.457
14.3	0.2715	0.272	0.271	0.241486	11.6947	7.63171	-119.562
14.33	0.27575	0.277	0.2745	0.236542	11.6055	6.7655	-114.518
14.38	0.26875	0.266	0.2715	0.234821	11.4888	5.63709	-107.977
14.42	0.26525	0.265	0.2655	0.230224	11.3876	4.66314	-102.357
14.47	0.265	0.265	0.265	0.223119	11.2829	3.66173	-96.6046
14.52	0.2665	0.267	0.266	0.232163	11.1578	2.46955	-89.7857
14.55	0.264	0.263	0.265	0.234215	11.0552	1.49675	-84.2451
14.6	0.26	0.259	0.261	0.229486	10.9662	0.656939	-79.4822
14.65	0.26125	0.262	0.2605	0.224841	10.8752	-0.1989	-74.6483
14.68	0.26125	0.261	0.2615	0.22973	10.7667	-1.21422	-68.9366
14.73	0.258	0.257	0.259	0.231728	10.6729	-2.08819	-64.0397
14.77	0.249836	0.261	0.259	0.229509	10.5948	-2.81235	-59.9983
14.82	0.26175	0.262	0.2615	0.230824	10.5346	-3.36911	-56.9031
14.87	0.26125	0.261	0.2615	0.230216	10.443	-4.21116	-52.2402
14.9	0.25875	0.258	0.2595	0.234805	10.3514	-5.05116	-47.6067
14.95	0.250634	0.262	0.26	0.229902	10.2808	-5.69531	-44.0672
15	0.259	0.258	0.26	0.228681	10.2198	-6.24946	-41.0337
15.03	0.255	0.254	0.256	0.224209	10.1308	-7.05498	-36.6409
15.08	0.2555	0.256	0.255	0.226284	10.0406	-7.86774	-32.2252
15.12	0.2575	0.258	0.257	0.224401	9.95538	-8.63358	-28.0794
15.17	0.2535	0.252	0.255	0.220189	9.85908	-9.49514	-23.4324
15.22	0.252	0.252	0.252	0.226403	9.76248	-10.3562	-18.8048
15.25	0.25125	0.251	0.2515	0.226993	9.68854	-11.0128	-15.2881
15.3	0.25325	0.254	0.2525	0.222344	9.61875	-11.6303	-11.9926
15.35	0.25175	0.251	0.2525	0.224592	9.53021	-12.4109	-7.84087
15.38	0.2525	0.253	0.252	0.22406	9.45273	-13.0916	-4.23302
15.43	0.24925	0.248	0.2505	0.222328	9.37194	-13.7989	-0.49741

15.47	0.245	0.244	0.246	0.221846	9.29579	-14.4631	2.99918
15.52	0.241	0.24	0.242	0.223764	9.23061	-15.0296	5.97171
15.57	0.24675	0.249	0.2445	0.221479	9.18235	-15.4477	8.15835
15.6	0.2475	0.247	0.248	0.223546	9.11199	-16.0553	11.3258
15.65	0.241354	0.25	0.2485	0.225561	9.04562	-16.6266	14.2938
15.7	0.24775	0.247	0.2485	0.224518	9.00208	-17	16.2282
15.73	0.2395	0.237	0.242	0.222639	8.93832	-17.5451	19.0416
15.78	0.234617	0.245	0.241	0.217851	8.89227	-17.9374	21.0602
15.83	0.245	0.245	0.245	0.222116	8.84675	-18.324	23.0434
15.87	0.242	0.241	0.243	0.22157	8.78493	-18.8473	25.7194
15.92	0.2425	0.243	0.242	0.217032	8.73001	-19.3107	28.0812
15.97	0.243	0.243	0.243	0.215394	8.66191	-19.8834	30.9913
16	0.243	0.243	0.243	0.217788	8.5885	-20.499	34.109
16.05	0.24225	0.242	0.2425	0.217489	8.52181	-21.0563	36.9232
16.1	0.24125	0.241	0.2415	0.219784	8.45669	-21.5989	39.6546
16.13	0.2395	0.239	0.24	0.218036	8.40054	-22.0652	41.9946
16.18	0.2375	0.237	0.238	0.217613	8.34474	-22.5272	44.3066
16.22	0.23325	0.232	0.2345	0.219722	8.29334	-22.9515	46.4229
16.27	0.228709	0.235	0.2335	0.217628	8.25859	-23.2375	47.8452
16.32	0.232263	0.24	0.2375	0.21929	8.23032	-23.4695	48.9958
16.35	0.23775	0.237	0.2385	0.217169	8.19742	-23.7386	50.3267
16.4	0.231261	0.239	0.238	0.216784	8.14553	-24.1619	52.4134
16.45	0.23825	0.238	0.2385	0.221265	8.10924	-24.4571	53.864
16.48	0.235	0.234	0.236	0.214249	8.06691	-24.8003	55.5459
16.53	0.23025	0.229	0.2315	0.210059	8.0155	-25.2159	57.5768
16.58	0.223451	0.229	0.229	0.212353	7.96579	-25.6167	59.5294
16.62	0.224561	0.23	0.2295	0.214182	7.93864	-25.8349	60.5895
16.67	0.22417	0.232	0.231	0.209509	7.91343	-26.037	61.5688
16.72	0.232	0.232	0.232	0.211549	7.87804	-26.3199	62.9355
16.75	0.22975	0.229	0.2305	0.197082	7.82897	-26.711	64.8195
16.8	0.223693	0.229	0.229	0.21308	7.75109	-27.33	67.7932
16.85	0.226334	0.233	0.231	0.215003	7.72595	-27.5293	68.7477
16.88	0.23075	0.23	0.2315	0.213083	7.69929	-27.74	69.7544
16.93	0.22625	0.225	0.2275	0.208927	7.65799	-28.0656	71.3053
16.97	0.222922	0.23	0.2275	0.211266	7.61774	-28.382	72.808
17.02	0.224077	0.231	0.2305	0.210732	7.59085	-28.5928	73.8067
17.07	0.22875	0.228	0.2295	0.215481	7.56026	-28.832	74.9366
17.1	0.222395	0.228	0.228	0.211186	7.53004	-29.0676	76.0468
17.15	0.2265	0.226	0.227	0.210691	7.50467	-29.2648	76.9734
17.2	0.222387	0.23	0.228	0.20916	7.46914	-29.5405	78.2648
17.23	0.22925	0.229	0.2295	0.211393	7.4396	-29.7689	79.3324
17.28	0.22825	0.228	0.2285	0.211292	7.39997	-30.0746	80.7568
17.33	0.221254	0.224	0.226	0.213762	7.36258	-30.3623	82.0936
17.37	0.219105	0.224	0.224	0.209316	7.34617	-30.4882	82.6772
17.42	0.21853	0.224	0.224	0.207591	7.32487	-30.6512	83.4307
17.47	0.219276	0.224	0.224	0.209827	7.30123	-30.8317	84.2628
17.5	0.22025	0.219	0.2215	0.20812	7.28095	-30.9861	84.9729
17.55	0.21629	0.221	0.22	0.20787	7.25508	-31.1826	85.8738
17.6	0.216849	0.22	0.2205	0.210046	7.23725	-31.3177	86.4917
17.63	0.216592	0.221	0.2205	0.208276	7.22294	-31.4258	86.985
17.68	0.22025	0.22	0.2205	0.204003	7.20556	-31.5568	87.5809

17.72	0.21775	0.217	0.2185	0.20013	7.17184	-31.8103	88.7315
17.77	0.211413	0.217	0.217	0.20024	7.13551	-32.0828	89.9648
17.82	0.213583	0.218	0.2175	0.205248	7.11263	-32.2539	90.7376
17.85	0.215	0.214	0.216	0.198484	7.09569	-32.3804	91.3071
17.9	0.211096	0.215	0.2145	0.203788	7.06234	-32.6287	92.4226
17.95	0.211666	0.216	0.2155	0.203498	7.04768	-32.7376	92.9103
17.98	0.206823	0.207	0.2115	0.201969	7.03142	-32.8581	93.4489
18.03	0.21375	0.216	0.2115	0.197731	7.02182	-32.929	93.7652
18.08	0.210987	0.212	0.214	0.206961	6.99037	-33.161	94.7967
18.12	0.207111	0.211	0.2115	0.198833	6.98252	-33.2187	95.0529
18.17	0.206895	0.211	0.211	0.198686	6.96649	-33.3364	95.5735
18.22	0.207057	0.214	0.2125	0.194671	6.95071	-33.452	96.0838
18.25	0.208602	0.21	0.212	0.203807	6.92706	-33.6248	96.8448
18.3	0.20656	0.21	0.21	0.199679	6.91796	-33.6911	97.136
18.35	0.208084	0.214	0.212	0.198251	6.905	-33.7854	97.5491
18.38	0.214	0.214	0.214	0.187899	6.8866	-33.9189	98.1326
18.43	0.208868	0.212	0.213	0.201602	6.83809	-34.27	99.6638
18.47	0.207222	0.212	0.212	0.197666	6.82468	-34.3669	100.085
18.52	0.207609	0.211	0.2115	0.200326	6.80715	-34.4932	100.633
18.57	0.2095	0.209	0.21	0.189955	6.79388	-34.5886	101.046
18.6	0.205721	0.207	0.208	0.202162	6.75851	-34.8423	102.142
18.65	0.207848	0.212	0.2095	0.202044	6.75212	-34.8881	102.339
18.7	0.212	0.212	0.212	0.187785	6.74176	-34.9621	102.657
18.73	0.20958	0.215	0.2135	0.20024	6.69883	-35.268	103.968
18.78	0.20914	0.213	0.214	0.20042	6.68238	-35.385	104.469
18.83	0.206934	0.21	0.2115	0.199303	6.66712	-35.4932	104.93
18.87	0.20735	0.21	0.21	0.202049	6.65385	-35.5871	105.33
18.92	0.20658	0.211	0.2105	0.198239	6.6447	-35.6518	105.605
18.97	0.20732	0.212	0.2115	0.198459	6.63039	-35.7526	106.032
19	0.2075	0.206	0.209	0.197422	6.61529	-35.8589	106.481
19.05	0.201459	0.205	0.2055	0.193876	6.59822	-35.9786	106.986
19.08	0.2035	0.203	0.204	0.190251	6.58547	-36.0679	107.361
19.13	0.198786	0.201	0.202	0.193359	6.56334	-36.2226	108.011
19.18	0.200026	0.204	0.2025	0.193579	6.55433	-36.2854	108.273
19.22	0.199686	0.203	0.2035	0.192558	6.54371	-36.3593	108.582
19.27	0.19949	0.201	0.202	0.195469	6.53205	-36.4403	108.92
19.32	0.200434	0.206	0.2035	0.191801	6.52552	-36.4856	109.108
19.35	0.203	0.202	0.204	0.192214	6.51158	-36.582	109.508
19.4	0.198981	0.203	0.2025	0.191444	6.49429	-36.7014	110.003
19.45	0.201308	0.201	0.202	0.200923	6.48228	-36.7841	110.344
19.48	0.197571	0.201	0.201	0.190713	6.48167	-36.7882	110.362
19.53	0.197781	0.202	0.2015	0.189843	6.4709	-36.8622	110.666
19.58	0.197108	0.2	0.201	0.190325	6.4585	-36.9471	111.014
19.62	0.195997	0.199	0.1995	0.189491	6.44798	-37.019	111.309
19.67	0.195986	0.199	0.199	0.189959	6.43796	-37.0874	111.588
19.72	0.198506	0.202	0.2005	0.193018	6.42873	-37.1502	111.844
19.75	0.196728	0.198	0.2	0.192184	6.42039	-37.2069	112.075
19.8	0.196416	0.201	0.1995	0.188749	6.41352	-37.2534	112.264
19.83	0.198973	0.203	0.202	0.19192	6.40201	-37.3313	112.579
19.88	0.198202	0.203	0.203	0.188606	6.39149	-37.4024	112.867
19.93	0.200294	0.205	0.204	0.191883	6.37727	-37.4983	113.253

19.97	0.199847	0.203	0.204	0.19254	6.36488	-37.5817	113.589
20.02	0.197431	0.201	0.202	0.189293	6.35418	-37.6535	113.877
20.07	0.20025	0.2	0.2005	0.1861	6.34234	-37.7329	114.196
20.1	0.197	0.196	0.198	0.185742	6.32188	-37.8698	114.743
20.15	0.19573	0.2	0.198	0.18919	6.3057	-37.9779	115.174
20.2	0.194198	0.196	0.198	0.188594	6.29637	-38.0401	115.422
20.23	0.192966	0.197	0.1965	0.185397	6.28842	-38.093	115.632
20.28	0.195754	0.2	0.1985	0.188763	6.27775	-38.1639	115.913
20.33	0.19325	0.191	0.1955	0.185646	6.26796	-38.2288	116.17
20.37	0.190991	0.194	0.1925	0.186471	6.25738	-38.2988	116.447
20.42	0.191301	0.194	0.194	0.185904	6.25113	-38.3401	116.609
20.47	0.191	0.19	0.192	0.17632	6.24372	-38.389	116.802
20.5	0.187976	0.19	0.19	0.183928	6.22368	-38.5209	117.319
20.55	0.189303	0.193	0.1915	0.183409	6.21819	-38.557	117.461
20.58	0.191588	0.196	0.1945	0.184263	6.21026	-38.6091	117.664
20.63	0.191461	0.195	0.1955	0.183884	6.20046	-38.6733	117.915
20.68	0.192109	0.196	0.1955	0.184828	6.19038	-38.7392	118.171
20.72	0.194298	0.202	0.199	0.181893	6.18076	-38.802	118.415
20.77	0.184745	0.181	0.1915	0.181734	6.16446	-38.9082	118.827
20.82	0.179239	0.179	0.18	0.178716	6.16053	-38.9338	118.926
20.85	0.176515	0.178	0.1785	0.173045	6.15985	-38.9382	118.943
20.9	0.178725	0.183	0.1805	0.172675	6.15538	-38.9672	119.055
20.93	0.178399	0.18	0.1815	0.173696	6.14764	-39.0173	119.248
20.98	0.179957	0.18	0.18	0.179872	6.14167	-39.0559	119.396
21.03	0.181948	0.186	0.183	0.176845	6.14156	-39.0566	119.399
21.07	0.18075	0.179	0.1825	0.173991	6.13516	-39.0979	119.557
21.12	0.182	0.183	0.181	0.190646	6.12674	-39.152	119.764
21.17	0.17775	0.176	0.1795	0.170544	6.13744	-39.0833	119.502
21.2	0.176728	0.176	0.176	0.178184	6.12858	-39.1401	119.718
21.25	0.173233	0.171	0.1735	0.175198	6.13036	-39.1287	119.675
21.28	0.17386	0.18	0.1755	0.17222	6.13274	-39.1135	119.617
21.33	0.178317	0.182	0.181	0.17195	6.13077	-39.1261	119.665
21.38	0.181704	0.183	0.1825	0.179613	6.12314	-39.1748	119.849
21.42	0.179769	0.179	0.181	0.179307	6.12065	-39.1906	119.908
21.47	0.174519	0.176	0.1775	0.170058	6.1201	-39.1941	119.922
21.52	0.177286	0.176	0.176	0.179857	6.11485	-39.2274	120.047
21.55	0.175317	0.174	0.175	0.176951	6.11786	-39.2083	119.975
21.6	0.177031	0.18	0.177	0.174092	6.11976	-39.1963	119.93
21.65	0.175127	0.176	0.178	0.17138	6.11636	-39.2178	120.01
21.68	0.177826	0.178	0.177	0.178477	6.11206	-39.2449	120.112
21.73	0.17623	0.176	0.177	0.175689	6.1128	-39.2402	120.094
21.78	0.179169	0.185	0.1805	0.177838	6.11219	-39.2441	120.109
21.82	0.180929	0.181	0.183	0.178788	6.11069	-39.2535	120.144
21.87	0.181689	0.184	0.1825	0.178566	6.10829	-39.2686	120.199
21.9	0.178315	0.178	0.181	0.175944	6.10481	-39.2904	120.28
21.95	0.178661	0.18	0.179	0.176984	6.10218	-39.3068	120.341
22	0.180152	0.18	0.18	0.180456	6.10033	-39.3184	120.384
22.03	0.179575	0.179	0.1795	0.180224	6.10066	-39.3163	120.376
22.08	0.179019	0.18	0.1795	0.177557	6.10137	-39.3119	120.36
22.13	0.178542	0.178	0.179	0.178626	6.09978	-39.3218	120.396
22.17	0.175836	0.175	0.1765	0.176007	6.09987	-39.3212	120.394

22.22	0.177782	0.18	0.1775	0.175847	6.10006	-39.3201	120.39
22.25	0.176492	0.175	0.1775	0.176975	6.09799	-39.3328	120.436
22.3	0.175798	0.177	0.176	0.174394	6.0985	-39.3297	120.425
22.35	0.178827	0.18	0.1785	0.177979	6.09702	-39.3388	120.458
22.38	0.1773	0.176	0.178	0.177899	6.09613	-39.3443	120.478
22.43	0.175786	0.176	0.176	0.175358	6.09676	-39.3405	120.464
22.48	0.17075	0.169	0.1725	0.176521	6.09632	-39.3432	120.474
22.52	0.172624	0.173	0.171	0.173873	6.10227	-39.3066	120.342
22.57	0.17208	0.169	0.171	0.176241	6.10355	-39.2987	120.313
22.62	0.173276	0.172	0.1705	0.177327	6.1078	-39.2727	120.22
22.65	0.175235	0.175	0.1735	0.177205	6.11191	-39.2476	120.129
22.7	0.174403	0.174	0.1745	0.174709	6.1139	-39.2354	120.086
22.75	0.173145	0.171	0.1725	0.175934	6.11421	-39.2335	120.079
22.78	0.171317	0.17	0.1705	0.17345	6.11699	-39.2166	120.018
22.83	0.174646	0.177	0.1735	0.173438	6.11911	-39.2037	119.972
22.87	0.173247	0.171	0.174	0.174741	6.11792	-39.2109	119.998
22.92	0.173258	0.173	0.172	0.174774	6.11939	-39.202	119.966
22.97	0.16775	0.166	0.1695	0.176036	6.12087	-39.193	119.934
23	0.169993	0.169	0.1675	0.17348	6.12893	-39.1442	119.761
23.05	0.17222	0.17	0.1695	0.177161	6.13231	-39.1238	119.689
23.1	0.171571	0.17	0.17	0.174713	6.13706	-39.0951	119.587
23.13	0.16325	0.161	0.1655	0.178427	6.14007	-39.077	119.523
23.18	0.16775	0.17	0.1655	0.175746	6.15452	-38.9899	119.216
23.22	0.170398	0.167	0.1685	0.175694	6.16209	-38.9443	119.055
23.27	0.17113	0.167	0.167	0.179389	6.16708	-38.9143	118.95
23.32	0.174306	0.175	0.171	0.176918	6.17482	-38.8678	118.787
23.35	0.16825	0.166	0.1705	0.178254	6.17726	-38.8532	118.735
23.4	0.164688	0.165	0.1655	0.163564	6.18654	-38.7976	118.541
23.45	0.16575	0.166	0.1655	0.17846	6.1855	-38.8038	118.562
23.48	0.164462	0.162	0.164	0.167386	6.19718	-38.7341	118.319
23.53	0.1635	0.164	0.163	0.177324	6.19985	-38.7181	118.263
23.58	0.16475	0.165	0.1645	0.19309	6.21242	-38.6432	118.003
23.62	0.1665	0.167	0.166	0.17799	6.23805	-38.4906	117.472
23.67	0.167843	0.163	0.165	0.175528	6.24839	-38.4291	117.259
23.7	0.166207	0.161	0.162	0.175621	6.25527	-38.3882	117.117
23.75	0.164	0.165	0.163	0.179344	6.26366	-38.3385	116.945
23.8	0.168161	0.161	0.163	0.180484	6.27727	-38.2578	116.666
23.83	0.16175	0.162	0.1615	0.178057	6.28814	-38.1935	116.444
23.88	0.1635	0.164	0.163	0.177977	6.30246	-38.1088	116.153
23.93	0.167057	0.16	0.162	0.17917	6.31511	-38.0341	115.896
23.97	0.16225	0.163	0.1615	0.179219	6.32564	-37.9719	115.682
24.02	0.163	0.163	0.163	0.180372	6.34033	-37.8854	115.385
24.07	0.1615	0.161	0.162	0.183966	6.35529	-37.7973	115.084
24.1	0.16325	0.164	0.1625	0.183786	6.37455	-37.6841	114.696
24.15	0.16475	0.165	0.1645	0.187317	6.39208	-37.5811	114.345
24.18	0.169348	0.163	0.164	0.181045	6.41125	-37.4687	113.961
24.23	0.163	0.163	0.163	0.197011	6.42114	-37.4107	113.763
24.28	0.16525	0.166	0.1645	0.185604	6.44978	-37.243	113.193
24.32	0.16	0.158	0.162	0.179409	6.46684	-37.1433	112.854
24.37	0.161	0.162	0.16	0.186678	6.48304	-37.0486	112.533
24.42	0.162	0.162	0.162	0.18404	6.50438	-36.9241	112.112

24.45	0.16125	0.161	0.1615	0.183937	6.52262	-36.8179	111.752
24.5	0.1595	0.159	0.16	0.181387	6.54131	-36.7091	111.385
24.55	0.1605	0.161	0.16	0.184968	6.55926	-36.6046	111.033
24.58	0.158	0.157	0.159	0.186053	6.57925	-36.4885	110.641
24.63	0.1585	0.159	0.158	0.183407	6.60206	-36.3561	110.196
24.68	0.15075	0.148	0.1535	0.18328	6.62224	-36.2392	109.803
24.72	0.154	0.156	0.152	0.184221	6.64847	-36.0873	109.294
24.77	0.15375	0.153	0.1545	0.18155	6.67273	-35.9469	108.823
24.8	0.156	0.157	0.155	0.185046	6.69495	-35.8185	108.394
24.85	0.15775	0.158	0.1575	0.182414	6.71807	-35.6851	107.948
24.9	0.1565	0.156	0.157	0.194527	6.73762	-35.5723	107.572
24.93	0.15675	0.157	0.1565	0.188041	6.76764	-35.3994	106.995
24.98	0.157	0.157	0.157	0.182933	6.79225	-35.2578	106.524
25.03	0.157	0.157	0.157	0.186496	6.81256	-35.141	106.136
25.07	0.1645	0.167	0.162	0.186324	6.83557	-35.0089	105.697
25.12	0.161	0.159	0.163	0.189975	6.85253	-34.9116	105.375
25.17	0.156	0.155	0.157	0.184943	6.87496	-34.783	104.949
25.2	0.15275	0.152	0.1535	0.184805	6.89729	-34.6552	104.527
25.25	0.15725	0.159	0.1555	0.18217	6.92192	-34.5143	104.062
25.28	0.161363	0.154	0.1565	0.173589	6.94099	-34.4054	103.703
25.33	0.15175	0.151	0.1525	0.18361	6.95031	-34.3522	103.527
25.38	0.15475	0.156	0.1535	0.187103	6.97451	-34.2142	103.074
25.42	0.1515	0.15	0.153	0.184481	6.99898	-34.0748	102.616
25.47	0.1545	0.156	0.153	0.18794	7.02384	-33.9334	102.152
25.5	0.15675	0.157	0.1565	0.185306	7.04894	-33.7907	101.685
25.55	0.154	0.153	0.155	0.188781	7.07029	-33.6694	101.288
25.6	0.14925	0.148	0.1505	0.189732	7.09621	-33.5224	100.807
25.63	0.148	0.148	0.148	0.189372	7.12625	-33.3521	100.252
25.68	0.154	0.156	0.152	0.188995	7.15684	-33.1789	99.6872
25.73	0.156	0.156	0.156	0.189947	7.18261	-33.0331	99.2127
25.77	0.160142	0.153	0.1545	0.172927	7.20752	-32.8923	98.755
25.82	0.1545	0.155	0.154	0.187583	7.21687	-32.8395	98.5837
25.87	0.1535	0.153	0.154	0.190997	7.24097	-32.7036	98.1429
25.9	0.15375	0.154	0.1535	0.191923	7.26819	-32.5502	97.6461
25.95	0.148	0.146	0.15	0.191634	7.2958	-32.3948	97.143
26	0.15125	0.153	0.1495	0.192448	7.32724	-32.2179	96.5721
26.03	0.15075	0.15	0.1515	0.192105	7.35682	-32.0517	96.0359
26.08	0.153	0.154	0.152	0.192966	7.3864	-31.8857	95.5008
26.13	0.157	0.158	0.156	0.190252	7.41489	-31.7259	94.9866
26.17	0.1535	0.152	0.155	0.193678	7.43851	-31.5936	94.5612
26.22	0.15575	0.157	0.1545	0.196969	7.46696	-31.4343	94.0501
26.25	0.15325	0.152	0.1545	0.190631	7.49604	-31.2717	93.5287
26.3	0.152	0.152	0.152	0.191589	7.52232	-31.1249	93.0584
26.35	0.15275	0.153	0.1525	0.193704	7.55007	-30.97	92.5631
26.38	0.1515	0.151	0.152	0.194589	7.57867	-30.8105	92.0536
26.43	0.1495	0.149	0.15	0.191835	7.60866	-30.6435	91.5206
26.48	0.1475	0.147	0.148	0.191504	7.63803	-30.48	90.9997
26.52	0.1485	0.149	0.148	0.192344	7.66844	-30.3109	90.4614
26.57	0.14975	0.15	0.1495	0.191986	7.69864	-30.1431	89.9281
26.62	0.15375	0.155	0.1525	0.19286	7.72764	-29.9822	89.4171
26.65	0.152	0.151	0.153	0.192594	7.75439	-29.8338	88.9466

26.7	0.14575	0.144	0.1475	0.193506	7.78208	-29.6805	88.4608
26.73	0.147	0.148	0.146	0.184684	7.81453	-29.5008	87.8924
26.78	0.1465	0.146	0.147	0.196469	7.84006	-29.3597	87.4464
26.83	0.1535	0.156	0.151	0.191202	7.87379	-29.1733	86.8583
26.87	0.15225	0.151	0.1535	0.194573	7.89915	-29.0333	86.417
26.92	0.151	0.151	0.151	0.191857	7.92753	-28.8768	85.9242
26.97	0.14725	0.146	0.1485	0.191573	7.95484	-28.7263	85.451
27	0.14825	0.149	0.1475	0.188831	7.98437	-28.5638	84.9404
27.05	0.146	0.145	0.147	0.186162	8.01131	-28.4156	84.4754
27.1	0.1465	0.147	0.146	0.187112	8.03789	-28.2695	84.0177
27.13	0.1455	0.145	0.146	0.192852	8.06468	-28.1225	83.5574
27.18	0.145	0.145	0.145	0.186456	8.0958	-27.9517	83.0236
27.22	0.1435	0.143	0.144	0.183785	8.12296	-27.8029	82.5588
27.27	0.1445	0.145	0.144	0.181145	8.14926	-27.6589	82.1096
27.32	0.1435	0.143	0.144	0.184579	8.1731	-27.5284	81.7032
27.35	0.14675	0.148	0.1455	0.187929	8.19974	-27.3828	81.2501
27.4	0.14875	0.149	0.1485	0.188866	8.22635	-27.2375	80.7984
27.45	0.143	0.141	0.145	0.186224	8.25218	-27.0965	80.3607
27.48	0.14175	0.142	0.1415	0.185935	8.27993	-26.9452	79.8915
27.53	0.142	0.142	0.142	0.186828	8.30819	-26.7913	79.4146
27.58	0.14875	0.151	0.1465	0.18051	8.33677	-26.6357	78.9333
27.62	0.136	0.136	0.1435	0.184039	8.35694	-26.526	78.5942
27.67	0.136	0.136	0.136	0.181268	8.38736	-26.3607	78.0839
27.7	0.136	0.136	0.136	0.176159	8.41592	-26.2057	77.6057
27.75	0.1345	0.134	0.135	0.179557	8.44117	-26.0687	77.1839
27.8	0.1325	0.132	0.133	0.176861	8.46939	-25.9158	76.7132
27.85	0.135	0.136	0.134	0.180183	8.49707	-25.7658	76.2524
27.88	0.133	0.132	0.134	0.183483	8.52516	-25.6138	75.7856
27.93	0.132	0.132	0.132	0.180683	8.55644	-25.4447	75.267
27.97	0.1335	0.134	0.133	0.183921	8.58648	-25.2824	74.7697
28.02	0.13025	0.129	0.1315	0.18352	8.61749	-25.115	74.2575
28.07	0.13425	0.136	0.1325	0.180673	8.65013	-24.939	73.7193
28.1	0.13675	0.137	0.1365	0.186349	8.67846	-24.7863	73.2529
28.15	0.13925	0.14	0.1385	0.183557	8.70863	-24.6238	72.7573
28.2	0.1445	0.146	0.143	0.180864	8.73549	-24.4793	72.3169
28.23	0.133	0.133	0.1395	0.181917	8.75746	-24.3612	71.9575
28.28	0.13375	0.134	0.1335	0.181548	8.78691	-24.2029	71.4763
28.32	0.13025	0.129	0.1315	0.182401	8.8156	-24.049	71.0088
28.37	0.13425	0.136	0.1325	0.199979	8.84678	-23.8818	70.5014
28.42	0.1345	0.134	0.135	0.184865	8.88593	-23.6719	69.8654
28.45	0.1325	0.132	0.133	0.185664	8.91584	-23.5118	69.3806
28.5	0.13875	0.141	0.1365	0.18521	8.94729	-23.3435	68.8717
28.55	0.13875	0.138	0.1395	0.188468	8.97468	-23.1971	68.4293
28.58	0.13275	0.131	0.1345	0.185666	9.00389	-23.041	67.9583
28.63	0.1355	0.137	0.134	0.182817	9.03488	-22.8756	67.4597
28.67	0.13625	0.136	0.1365	0.183666	9.0625	-22.7283	67.0161
28.72	0.1345	0.134	0.135	0.195314	9.09008	-22.5813	66.574
28.77	0.13925	0.141	0.1375	0.186296	9.12533	-22.3936	66.0099
28.8	0.14175	0.142	0.1415	0.171535	9.15251	-22.249	65.5758
28.85	0.139	0.138	0.14	0.187117	9.16967	-22.1578	65.3023
28.9	0.1365	0.136	0.137	0.186742	9.19729	-22.011	64.8628

28.93	0.14125	0.143	0.1395	0.183929	9.22604	-21.8584	64.4063
28.98	0.1385	0.137	0.14	0.190849	9.25038	-21.7293	64.0205
29.03	0.14075	0.142	0.1395	0.18799	9.28014	-21.5716	63.5496
29.07	0.14125	0.141	0.1415	0.187619	9.3069	-21.4299	63.127
29.12	0.1425	0.143	0.142	0.178864	9.33309	-21.2914	62.7141
29.17	0.1385	0.137	0.14	0.188305	9.35356	-21.1831	62.3921
29.2	0.1415	0.143	0.14	0.189093	9.38151	-21.0355	61.9531
29.25	0.1445	0.145	0.144	0.192311	9.40813	-20.895	61.5358
29.28	0.142	0.141	0.143	0.191815	9.43478	-20.7544	61.1188
29.33	0.1425	0.143	0.142	0.188987	9.46247	-20.6085	60.6864
29.38	0.14375	0.144	0.1435	0.188421	9.48822	-20.4728	60.2849
29.42	0.14325	0.143	0.1435	0.188986	9.51289	-20.343	59.9011
29.47	0.143	0.143	0.143	0.18843	9.53807	-20.2107	59.5101
29.52	0.1415	0.141	0.142	0.191179	9.56299	-20.0797	59.1236
29.55	0.138	0.137	0.139	0.18615	9.59017	-19.937	58.7031
29.6	0.137	0.137	0.137	0.188858	9.61642	-19.7994	58.2977
29.65	0.13475	0.134	0.1355	0.188192	9.6446	-19.6517	57.8633
29.68	0.13775	0.139	0.1365	0.183104	9.67354	-19.5001	57.4179
29.73	0.1345	0.133	0.136	0.18586	9.69801	-19.372	57.0418
29.78	0.13675	0.138	0.1355	0.183011	9.72564	-19.2275	56.6182
29.82	0.14325	0.145	0.1415	0.180247	9.75044	-19.0979	56.2386
29.87	0.134	0.134	0.1395	0.183147	9.7702	-18.9947	55.9366
29.9	0.13625	0.137	0.1355	0.180337	9.79638	-18.8582	55.5374
29.95	0.146372	0.125	0.131	0.183116	9.81977	-18.7362	55.1812
30	0.13175	0.134	0.1295	0.182774	9.83921	-18.6349	54.8858

O	DKEST	INVK	INVKAVE	DKBAL
4.00E-02	2.50E-02	2.50E-02	1.25E-02	4.07E-04
9.00E-02	5.00E-02	5.00E-02	3.75E-02	8.13E-04
0.13	0.127	0.127	8.85E-02	1.22E-03
0.17	0.149	0.149	0.138	1.05E-02
0.22	-1.60E-02	-1.60E-02	6.65E-02	3.85E-02
0.25	-1.00E-03	-1.00E-03	-8.50E-03	4.88E-02
0.3	0.277	0.277	0.138	6.94E-02
0.33	0.156	0.156	0.2165	8.84E-02
0.38	0.195	0.195	0.1755	8.83E-02
0.42	0.1875	0.185	0.19	9.74E-02
0.47	0.153	0.153	0.169	0.115662
0.5	0.254	0.254	0.2035	0.142348
0.53	0.295	0.295	0.2745	0.165208
0.58	0.191814	9.00E-02	0.1925	0.191128
0.63	0.492	0.492	0.291	0.216743
0.67	0.267	0.267	0.3795	0.24122
0.7	0.341	0.341	0.304	0.239309
0.75	0.296	0.296	0.3185	0.252867
0.8	0.285388	0.286	0.291	0.279165
0.83	0.543	0.543	0.4145	0.306373
0.87	0.352	0.352	0.4475	0.329028
0.92	0.347918	0.358	0.355	0.330755
0.97	0.34304	0.331	0.3445	0.341581
1	0.33175	0.332	0.3315	0.368787
1.05	0.388536	0.401	0.3665	0.398108
1.08	0.435336	0.48	0.4405	0.430173
1.13	0.562	0.562	0.521	0.474297
1.17	0.50215	0.51	0.536	0.494299
1.22	0.529673	0.562	0.536	0.523347
1.25	0.549207	0.522	0.542	0.556414
1.3	0.59539	0.605	0.5635	0.58578
1.33	0.625634	0.636	0.6205	0.6204
1.38	0.654175	0.675	0.6555	0.652849
1.42	0.615	0.615	0.645	0.687466
1.47	0.711127	0.698	0.6565	0.724254
1.5	0.716652	0.694	0.696	0.759955
1.55	0.7075	0.712	0.703	0.796739
1.58	0.73	0.736	0.724	0.832742
1.63	0.7795	0.794	0.765	0.884084
1.68	0.82325	0.833	0.8135	0.898671
1.72	0.80525	0.796	0.8145	0.919377
1.77	0.835	0.848	0.822	0.929069
1.8	0.8405	0.838	0.843	0.93751
1.85	0.85525	0.861	0.8495	0.943507
1.88	0.822	0.809	0.835	0.947049
1.93	0.83075	0.838	0.8235	0.951819
1.98	0.856	0.862	0.85	0.961484

2.02	0.88593	0.842	0.852	0.963791
2.07	0.86525	0.873	0.8575	0.969771
2.1	0.873	0.873	0.873	0.973291
2.15	0.895193	0.849	0.861	0.975579
2.18	0.87075	0.878	0.8635	0.969293
2.23	0.851	0.842	0.86	0.950745
2.27	0.85925	0.865	0.8535	0.970175
2.32	0.86575	0.866	0.8655	0.96632
2.35	0.863	0.862	0.864	0.953879
2.4	0.85225	0.849	0.8555	0.959808
2.45	0.85125	0.852	0.8505	0.959609
2.48	0.86025	0.863	0.8575	0.953278
2.53	0.8645	0.865	0.864	0.953059
2.58	0.832	0.821	0.843	0.952826
2.62	0.83525	0.84	0.8305	0.946481
2.67	0.83325	0.831	0.8355	0.948699
2.7	0.82275	0.82	0.8255	0.946012
2.75	0.8455	0.854	0.837	0.948223
2.8	0.85625	0.857	0.8555	0.954082
2.83	0.879449	0.839	0.848	0.951345
2.88	0.84725	0.85	0.8445	0.951057
2.92	0.85525	0.857	0.8535	0.936051
2.97	0.875099	0.835	0.846	0.944298
3.02	0.853	0.859	0.847	0.941523
3.05	0.786	0.786	0.8225	0.943611
3.1	0.82125	0.833	0.8095	0.943288
3.13	0.83225	0.832	0.8325	0.942932
3.18	0.84325	0.847	0.8395	0.942558
3.23	0.8425	0.841	0.844	0.944598
3.27	0.8545	0.859	0.85	0.947844
3.32	0.856	0.855	0.857	0.94737
3.35	0.86025	0.862	0.8585	0.952992
3.4	0.875108	0.832	0.847	0.946323
3.45	0.85075	0.857	0.8445	0.945801
3.48	0.876903	0.838	0.8475	0.94521
3.53	0.84775	0.851	0.8445	0.947062
3.57	0.874305	0.834	0.8425	0.946414
3.62	0.853896	0.805	0.8195	0.937187
3.67	0.8245	0.831	0.818	0.934123
3.7	0.84825	0.854	0.8425	0.950592
3.75	0.871621	0.827	0.8405	0.947364
3.78	0.85775	0.868	0.8475	0.949048
3.83	0.885212	0.849	0.8585	0.948136
3.88	0.84675	0.846	0.8475	0.947197
3.92	0.843	0.842	0.844	0.943763
3.97	0.84575	0.847	0.8445	0.945186
4	0.863362	0.815	0.831	0.944086
4.05	0.83975	0.848	0.8315	0.946707
4.1	0.84725	0.847	0.8475	0.939379
4.13	0.868901	0.826	0.8365	0.944203
4.18	0.83425	0.837	0.8315	0.949035
4.23	0.849	0.853	0.845	0.943975
4.27	0.8515	0.851	0.852	0.948527
4.32	0.8435	0.841	0.846	0.944393
4.37	0.8305	0.827	0.834	0.942675
4.4	0.8315	0.833	0.83	0.937277
4.45	0.8345	0.835	0.834	0.941566
4.5	0.832	0.831	0.833	0.943283
4.53	0.84825	0.854	0.8425	0.943681

4.58	0.876381	0.834	0.844	0.951142
4.63	0.8325	0.832	0.833	0.942661
4.67	0.83875	0.841	0.8365	0.946321
4.72	0.835	0.833	0.837	0.943641
4.77	0.836	0.837	0.835	0.949444
4.8	0.831	0.829	0.833	0.946462
4.85	0.8335	0.835	0.832	0.943391
4.9	0.83275	0.832	0.8335	0.94256
4.93	0.832	0.832	0.832	0.94277
4.98	0.83125	0.831	0.8315	0.941563
5.03	0.82725	0.826	0.8285	0.941406
5.07	0.81925	0.817	0.8215	0.933746
5.12	0.814	0.813	0.815	0.929678
5.17	0.8055	0.803	0.808	0.923069
5.2	0.7955	0.793	0.798	0.909065
5.25	0.78925	0.788	0.7905	0.904824
5.28	0.78125	0.779	0.7835	0.895647
5.33	0.77675	0.776	0.7775	0.893782
5.38	0.773	0.772	0.774	0.877157
5.42	0.7675	0.766	0.769	0.884928
5.47	0.763	0.762	0.764	0.880381
5.5	0.75525	0.753	0.7575	0.873317
5.55	0.75075	0.75	0.7515	0.86869
5.58	0.74175	0.739	0.7445	0.857886
5.63	0.736	0.735	0.737	0.853208
5.68	0.72975	0.728	0.7315	0.848501
5.72	0.72425	0.723	0.7255	0.843766
5.77	0.717	0.715	0.719	0.835312
5.8	0.71275	0.712	0.7135	0.828092
5.85	0.70525	0.703	0.7075	0.823264
5.88	0.69625	0.694	0.6985	0.812342
5.93	0.691	0.69	0.692	0.810004
5.98	0.68475	0.683	0.6865	0 805211
6.02	0.67775	0.676	0.6795	0.794286
6.07	0.6715	0.67	0.673	0.795606
6.1	0.664	0.662	0.666	0.784684
6.15	0.659	0.658	0.66	0.77989
6.2	0.6505	0.648	0.653	0.768971
6.23	0.6435	0.642	0.645	0.76176
6.28	0.636	0.634	0.638	0.753317
6.33	0.63025	0.629	0.6315	0.748588
6.37	0.6215	0.619	0.624	0.741404
6.42	0.6145	0.613	0.616	0.733025
6.45	0.60925	0.608	0.6105	0.73202
6.5	0.6065	0.606	0.607	0.729785
6.55	0.60525	0.605	0.6055	0.722637
6.58	0.599	0.597	0.601	0.720347
6.63	0.5925	0.591	0.594	0.713174
6.67	0.588	0.587	0.589	0.708467
6.72	0.58475	0.584	0.5855	0.706204
6.77	0.58025	0.579	0.5815	0.699037
6.8	0.57525	0.574	0.5765	0.696764
6.85	0.574	0.574	0.574	0.692043
6.88	0.56725	0.565	0.5695	0.687295
6.93	0.5605	0.559	0.562	0.676446
6.97	0.55525	0.554	0.5565	0.669296
7.02	0.5525	0.552	0.553	0.673173
7.07	0.55125	0.551	0.5515	0.672145
7.1	0.55025	0.55	0.5505	0.669865

7.15	0.54625	0.545	0.5475	0.668784
7.18	0.5435	0.543	0.544	0.66403
7.23	0.54375	0.544	0.5435	0.673964
7.28	0.54025	0.539	0.5415	0.660589
7.32	0.536	0.535	0.537	0.655786
7.37	0.535	0.535	0.535	0.653427
7.4	0.529	0.527	0.531	0.652267
7.45	0.524	0.523	0.525	0.643781
7.5	0.52375	0.524	0.5235	0.642655
7.53	0.52025	0.519	0.5215	0.643945
7.58	0.51825	0.518	0.5185	0.641556
7.63	0.515	0.514	0.516	0.634256
7.67	0.511	0.51	0.512	0.631851
7.72	0.5115	0.512	0.511	0.633117
7.75	0.50525	0.503	0.5075	0.628225
7.8	0.503	0.503	0.503	0.635615
7.83	0.4985	0.497	0.5	0.62706
7.88	0.494	0.493	0.495	0.625866
7.93	0.49075	0.49	0.4915	0.617332
7.97	0.48775	0.487	0.4885	0.610018
8.02	0.48475	0.484	0.4855	0.60515
8.07	0.48175	0.481	0.4825	0.602734
8.1	0.48025	0.48	0.4805	0.60154
8.15	0.4785	0.478	0.479	0.592978
8.18	0.47425	0.473	0.4755	0.597887
8.23	0.47375	0.474	0.4735	0.592999
8.28	0.47025	0.469	0.4715	0.583194
8.32	0.46675	0.466	0.4675	0.585642
8.37	0.4675	0.468	0.467	0.58441
8.4	0.46125	0.459	0.4635	0.573355
8.45	0.45675	0.456	0.4575	0.57703
8.48	0.45225	0.451	0.4535	0.572134
8.53	0.45025	0.45	0.4505	0.577047
8.58	0.45	0.45	0.45	0.566032
8.62	0.44625	0.445	0.4475	0.563575
8.67	0.4495	0.451	0.448	0.562346
8.7	0.44125	0.438	0.4445	0.557398
8.75	0.44325	0.445	0.4415	0.558626
8.8	0.439	0.437	0.441	0.556128
8.83	0.4325	0.431	0.434	0.554929
8.88	0.4325	0.433	0.432	0.552521
8.93	0.4345	0.435	0.434	0.545098
8.97	0.429	0.427	0.431	0.545144
9.02	0.42775	0.428	0.4275	0.543964
9.05	0.4235	0.422	0.425	0.541518
9.1	0.422	0.422	0.422	0.539088
9.13	0.4175	0.416	0.419	0.537899
9.18	0.416	0.416	0.416	0.532978
9.23	0.41675	0.417	0.4165	0.531796
9.27	0.41475	0.414	0.4155	0.535592
9.32	0.4155	0.416	0.415	0.530635
9.35	0.40925	0.407	0.4115	0.525655
9.4	0.40775	0.408	0.4075	0.524456
9.45	0.4065	0.406	0.407	0.521998
9.48	0.406	0.406	0.406	0.520787
9.53	0.4045	0.404	0.405	0.51831
9.58	0.39875	0.397	0.4005	0.513331
9.62	0.39475	0.394	0.3955	0.512126
9.67	0.394	0.394	0.394	0.497175

9.7	0.394	0.394	0.394	0.507215
9.75	0.391	0.39	0.392	0.50849
9.78	0.38475	0.383	0.3865	0.507276
9.83	0.3875	0.389	0.386	0.502336
9.88	0.38975	0.39	0.3895	0.49736
9.92	0.3885	0.388	0.389	0.501113
9.97	0.3895	0.39	0.389	0.502364
10	0.3885	0.388	0.389	0.501093
10.05	0.385	0.384	0.386	0.498571
10.1	0.387	0.388	0.386	0.49731
10.13	0.38275	0.381	0.3845	0.494764
10.18	0.3795	0.379	0.38	0.489736
10.23	0.376	0.375	0.377	0.488463
10.27	0.37275	0.372	0.3735	0.483451
10.32	0.36975	0.369	0.3705	0.474694
10.35	0.369	0.369	0.369	0.482192
10.4	0.363	0.361	0.365	0.483432
10.45	0.364	0.365	0.363	0.484703
10.48	0.36575	0.366	0.3655	0.475947
10.53	0.36375	0.363	0.3645	0.477176
10.57	0.3615	0.361	0.362	0.47591
10.62	0.3565	0.355	0.358	0.470893
10.67	0.355	0.355	0.355	0.472151
10.7	0.358	0.359	0.357	0.469651
10.75	0.35675	0.356	0.3575	0.470874
10.8	0.3545	0.354	0.355	0.459603
10.83	0.354	0.354	0.354	0.46458
10.88	0.3525	0.352	0.353	0.465801
10.92	0.35125	0.351	0.3515	0.46327
10.97	0.34575	0.344	0.3475	0.458238
11.02	0.34625	0.347	0.3455	0.459481
11.05	0.34775	0.348	0.3475	0.445704
11.1	0.34575	0.345	0.3465	0.458164
11.15	0.34425	0.344	0.3445	0.46938
11.18	0.34325	0.343	0.3435	0.454345
11.23	0.34375	0.344	0.3435	0.453053
11.27	0.341	0.34	0.342	0.454255
11.32	0.3385	0.338	0.339	0.445462
11.37	0.338	0.338	0.338	0.450425
11.4	0.3365	0.336	0.337	0.447882
11.45	0.33525	0.335	0.3355	0.446588
11.5	0.34025	0.342	0.3385	0.444045
11.53	0.33675	0.335	0.3385	0.438963
11.58	0.332	0.331	0.333	0.44015
11.62	0.33025	0.33	0.3305	0.441356
11.67	0.33075	0.331	0.3305	0.430062
11.72	0.334	0.335	0.333	0.440006
11.75	0.329	0.327	0.331	0.423674
11.8	0.33075	0.332	0.3295	0.429868
11.85	0.326	0.324	0.328	0.434788
11.88	0.3255	0.326	0.325	0.429738
11.93	0.32225	0.321	0.3235	0.437177
11.97	0.32025	0.32	0.3205	0.432128
12.02	0.32375	0.325	0.3225	0.42708
12.07	0.32125	0.32	0.3225	0.427007
12.1	0.317	0.316	0.318	0.421948
12.15	0.3145	0.314	0.315	0.423207
12.18	0.31475	0.315	0.3145	0.422082
12.23	0.30975	0.308	0.3115	0.419648

12.28	0.314	0.316	0.312	0.421152
12.32	0.313	0.312	0.314	0.420011
12.37	0.31125	0.311	0.3115	0.414963
12.42	0.3095	0.309	0.31	0.41644
12.45	0.306	0.305	0.307	0.417925
12.5	0.30425	0.304	0.3045	0.412897
12.55	0.30025	0.299	0.3015	0.414395
12.58	0.30275	0.304	0.3015	0.411998
12.63	0.30175	0.301	0.3025	0.416103
12.67	0.2995	0.299	0.3	0.408471
12.72	0.30125	0.302	0.3005	0.416505
12.77	0.30125	0.301	0.3015	0.404947
12.8	0.2995	0.299	0.3	0.409052
12.85	0.2975	0.297	0.298	0.404023
12.88	0.29625	0.296	0.2965	0.405526
12.93	0.29525	0.295	0.2955	0.404421
12.98	0.2965	0.297	0.296	0.405927
13.02	0.29625	0.296	0.2965	0.407423
13.07	0.29525	0.295	0.2955	0.405006
13.12	0.29425	0.294	0.2945	0.403896
13.15	0.29175	0.291	0.2925	0.401483
13.2	0.291	0.291	0.291	0.402992
13.25	0.29325	0.294	0.2925	0.400589
13.28	0.2895	0.288	0.291	0.402084
13.33	0.28875	0.289	0.2885	0.40099
13.37	0.286	0.285	0.287	0.398587
13.42	0.27825	0.276	0.2805	0.400113
13.47	0.2835	0.286	0.281	0.392542
13.5	0.28675	0.287	0.2865	0.396677
13.55	0.28475	0.284	0.2855	0.402106
13.58	0.28325	0.283	0.2835	0.399715
13.63	0.2815	0.281	0.282	0.394716
13.68	0.278	0.277	0.279	0.39625
13.72	0.2815	0.283	0.28	0.391274
13.77	0.2815	0.281	0.282	0.392801
13.82	0.28175	0.282	0.2815	0.394332
13.85	0.27825	0.277	0.2795	0.389334
13.9	0.27625	0.276	0.2765	0.384351
13.93	0.276	0.276	0.276	0.388512
13.98	0.27525	0.275	0.2755	0.380924
14.03	0.27575	0.276	0.2755	0.389
14.07	0.27525	0.275	0.2755	0.386633
14.12	0.27125	0.27	0.2725	0.385574
14.17	0.2685	0.268	0.269	0.38323
14.2	0.271	0.272	0.27	0.384811
14.25	0.2705	0.27	0.271	0.382462
14.3	0.2715	0.272	0.271	0.387947
14.33	0.27575	0.277	0.2745	0.382983
14.38	0.26875	0.266	0.2715	0.380609
14.42	0.26525	0.265	0.2655	0.37567
14.47	0.265	0.265	0.265	0.368124
14.52	0.2665	0.267	0.266	0.376242
14.55	0.264	0.263	0.265	0.377827
14.6	0.26	0.259	0.261	0.372902
14.65	0.26125	0.262	0.2605	0.367992
14.68	0.26125	0.261	0.2615	0.372209
14.73	0.258	0.257	0.259	0.37382
14.77	0.26	0.261	0.259	0.371532
14.82	0.26175	0.262	0.2615	0.373145

14.87	0.26125	0.261	0.2615	0.372146
14.9	0.25875	0.258	0.2595	0.376312
14.95	0.261	0.262	0.26	0.371412
15	0.259	0.258	0.26	0.370385
15.03	0.255	0.254	0.256	0.365488
15.08	0.2555	0.256	0.255	0.367081
15.12	0.2575	0.258	0.257	0.364788
15.17	0.2535	0.252	0.255	0.359899
15.22	0.252	0.252	0.252	0.36539
15.25	0.25125	0.251	0.2515	0.365706
15.3	0.25325	0.254	0.2525	0.360847
15.35	0.25175	0.251	0.2525	0.362455
15.38	0.2525	0.253	0.252	0.361484
15.43	0.24925	0.248	0.2505	0.359212
15.47	0.245	0.244	0.246	0.358256
15.52	0.241	0.24	0.242	0.359906
15.57	0.24675	0.249	0.2445	0.357693
15.6	0.2475	0.247	0.248	0.359336
15.65	0.24925	0.25	0.2485	0.360983
15.7	0.24775	0.247	0.2485	0.360035
15.73	0.2395	0.237	0.242	0.357801
15.78	0.243	0.245	0.241	0.353017
15.83	0.245	0.245	0.245	0.357275
15.87	0.242	0.241	0.243	0.356352
15.92	0.2425	0.243	0.242	0.351561
15.97	0.243	0.243	0.243	0.34936
16	0.243	0.243	0.243	0.351042
16.05	0.24225	0.242	0.2425	0.350141
16.1	0.24125	0.241	0.2415	0.351834
16.13	0.2395	0.239	0.24	0.349649
16.18	0.2375	0.237	0.238	0.348769
16.22	0.23325	0.232	0.2345	0.35049
16.27	0.23425	0.235	0.2335	0.348349
16.32	0.23875	0.24	0.2375	0.350088
16.35	0.23775	0.237	0.2385	0.347924
16.4	0.2385	0.239	0.238	0.347067
16.45	0.23825	0.238	0.2385	0.35139
16.48	0.235	0.234	0.236	0.344064
16.53	0.23025	0.229	0.2315	0.339345
16.58	0.229	0.229	0.229	0.341123
16.62	0.22975	0.23	0.2295	0.342908
16.67	0.2315	0.232	0.231	0.338218
16.72	0.232	0.232	0.232	0.339998
16.75	0.22975	0.229	0.2305	0.324949
16.8	0.229	0.229	0.229	0.339696
16.85	0.232	0.233	0.231	0.3415
16.88	0.23075	0.23	0.2315	0.339409
16.93	0.22625	0.225	0.2275	0.334739
16.97	0.22875	0.23	0.2275	0.336567
17.02	0.23075	0.231	0.2305	0.335795
17.07	0.22875	0.228	0.2295	0.340204
17.1	0.228	0.228	0.228	0.33556
17.15	0.2265	0.226	0.227	0.334807
17.2	0.229	0.23	0.228	0.332772
17.23	0.22925	0.229	0.2295	0.334611
17.28	0.22825	0.228	0.2285	0.333867
17.33	0.225	0.224	0.226	0.335721
17.37	0.224	0.224	0.224	0.331116
17.42	0.224	0.224	0.224	0.329109

17.47	0.224	0.224	0.224	0.330993
17.5	0.22025	0.219	0.2215	0.328994
17.55	0.2205	0.221	0.22	0.328313
17.6	0.22025	0.22	0.2205	0.330223
17.63	0.22075	0.221	0.2205	0.328256
17.68	0.22025	0.22	0.2205	0.3237
17.72	0.21775	0.217	0.2185	0.319151
17.77	0.217	0.217	0.217	0.318504
17.82	0.21775	0.218	0.2175	0.323045
17.85	0.215	0.214	0.216	0.315933
17.9	0.21475	0.215	0.2145	0.320494
17.95	0.21575	0.216	0.2155	0.319877
17.98	0.20925	0.207	0.2115	0.317966
18.03	0.21375	0.216	0.2115	0.3135
18.08	0.213	0.212	0.214	0.321965
18.12	0.21125	0.211	0.2115	0.313611
18.17	0.211	0.211	0.211	0.313036
18.22	0.21325	0.214	0.2125	0.308584
18.25	0.211	0.21	0.212	0.317077
18.3	0.21	0.21	0.21	0.312639
18.35	0.213	0.214	0.212	0.310799
18.38	0.214	0.214	0.214	0.299886
18.43	0.2125	0.212	0.213	0.312284
18.47	0.212	0.212	0.212	0.307861
18.52	0.21125	0.211	0.2115	0.309921
18.57	0.2095	0.209	0.21	0.299038
18.6	0.2075	0.207	0.208	0.310183
18.65	0.21075	0.212	0.2095	0.309687
18.7	0.212	0.212	0.212	0.294937
18.73	0.21425	0.215	0.2135	0.306091
18.78	0.2135	0.213	0.214	0.305586
18.83	0.21075	0.21	0.2115	0.3038
18.87	0.21	0.21	0.21	0.305912
18.92	0.21075	0.211	0.2105	0.301557
18.97	0.21175	0.212	0.2115	0.301091
19	0.2075	0.206	0.209	0.299331
19.05	0.20525	0.205	0.2055	0.295006
19.08	0.2035	0.203	0.204	0.290695
19.13	0.2015	0.201	0.202	0.292872
19.18	0.20325	0.204	0.2025	0.292472
19.22	0.20325	0.203	0.2035	0.290776
19.27	0.2015	0.201	0.202	0.292972
19.32	0.20475	0.206	0.2035	0.288707
19.35	0.203	0.202	0.204	0.28832
19.4	0.20275	0.203	0.2025	0.286657
19.45	0.2015	0.201	0.202	0.295357
19.48	0.201	0.201	0.201	0.284646
19.53	0.20175	0.202	0.2015	0.283008
19.58	0.2005	0.2	0.201	0.282669
19.62	0.19925	0.199	0.1995	0.281048
19.67	0.199	0.199	0.199	0.28073
19.72	0.20125	0.202	0.2005	0.283012
19.75	0.199	0.198	0.2	0.281407
19.8	0.20025	0.201	0.1995	0.277231
19.83	0.2025	0.203	0.202	0.279528
19.88	0.203	0.203	0.203	0.276348
19.93	0.2045	0.205	0.204	0.277653
19.97	0.2035	0.203	0.204	0.277365
20.02	0.2015	0.201	0.202	0.273207

20.07	0.20025	0.2	0.2005	0.269062
20.1	0.197	0.196	0.198	0.267517
20.15	0.199	0.2	0.198	0.269876
20.2	0.197	0.196	0.198	0.268349
20.23	0.19675	0.197	0.1965	0.264251
20.28	0.19925	0.2	0.1985	0.266631
20.33	0.19325	0.191	0.1955	0.262536
20.37	0.19325	0.194	0.1925	0.262361
20.42	0.194	0.194	0.194	0.260889
20.47	0.191	0.19	0.192	0.250361
20.5	0.19	0.19	0.19	0.256688
20.55	0.19225	0.193	0.1915	0.255253
20.58	0.19525	0.196	0.1945	0.255113
20.63	0.19525	0.195	0.1955	0.253676
20.68	0.19575	0.196	0.1955	0.253544
20.72	0.2005	0.202	0.199	0.24953
20.77	0.181	0.181	0.1915	0.248096
20.82	0.1795	0.179	0.18	0.244143
20.85	0.17825	0.178	0.1785	0.237618
20.9	0.18175	0.183	0.1805	0.236289
20.93	0.18075	0.18	0.1815	0.236248
20.98	0.18	0.18	0.18	0.241402
21.03	0.1845	0.186	0.183	0.237499
21.07	0.18075	0.179	0.1825	0.233586
21.12	0.182	0.183	0.181	0.249128
21.17	0.17775	0.176	0.1795	0.228409
21.2	0.176	0.176	0.176	0.234914
21.25	0.17225	0.171	0.1735	0.231068
21.28	0.17775	0.18	0.1755	0.227248
21.33	0.1815	0.182	0.181	0.226001
21.38	0.18275	0.183	0.1825	0.232524
21.42	0.18	0.179	0.181	0.231205
21.47	0.17675	0.176	0.1775	0.220991
21.52	0.176	0.176	0.176	0.229697
21.55	0.1745	0.174	0.175	0.225913
21.6	0.1785	0.18	0.177	0.222143
21.65	0.177	0.176	0.178	0.218362
21.68	0.1775	0.178	0.177	0.224361
21.73	0.1765	0.176	0.177	0.220605
21.78	0.18275	0.185	0.1805	0.221743
21.82	0.182	0.181	0.183	0.221639
21.87	0.18325	0.184	0.1825	0.220336
21.9	0.1795	0.178	0.181	0.216593
21.95	0.1795	0.18	0.179	0.216533
22	0.18	0.18	0.18	0.21892
22.03	0.17925	0.179	0.1795	0.217655
22.08	0.17975	0.18	0.1795	0.21396
22.13	0.1785	0.178	0.179	0.21393
22.17	0.17575	0.175	0.1765	0.210254
22.22	0.17875	0.18	0.1775	0.209039
22.25	0.17625	0.175	0.1775	0.209037
22.3	0.1765	0.177	0.176	0.205396
22.35	0.17925	0.18	0.1785	0.207859
22.38	0.177	0.176	0.178	0.206662
22.43	0.176	0.176	0.176	0.203046
22.48	0.181533	0.169	0.1725	0.203099
22.52	0.172	0.173	0.171	0.199521
22.57	0.17	0.169	0.171	0.200823
22.62	0.17125	0.172	0.1705	0.200925

22.65	0.17425	0.175	0.1735	0.199808
22.7	0.17425	0.174	0.1745	0.196249
22.75	0.17175	0.171	0.1725	0.196361
22.78	0.17025	0.17	0.1705	0.192833
22.83	0.17525	0.177	0.1735	0.191753
22.87	0.178962	0.171	0.174	0.191885
22.92	0.1725	0.173	0.172	0.190821
22.97	0.16775	0.166	0.1695	0.190981
23	0.16825	0.169	0.1675	0.187512
23.05	0.16975	0.17	0.1695	0.190142
23.1	0.17	0.17	0.17	0.186678
23.13	0.16325	0.161	0.1655	0.189324
23.18	0.16775	0.17	0.1655	0.185904
23.22	0.173469	0.167	0.1685	0.184908
23.27	0.167	0.167	0.167	0.187588
23.32	0.173	0.175	0.171	0.184178
23.35	0.16825	0.166	0.1705	0.184412
23.4	0.166441	0.165	0.1655	0.168822
23.45	0.16575	0.166	0.1655	0.182526
23.48	0.165539	0.162	0.164	0.170616
23.53	0.1635	0.164	0.163	0.179464
23.58	0.16475	0.165	0.1645	0.194419
23.62	0.1665	0.167	0.166	0.178877
23.67	0.167847	0.163	0.165	0.175541
23.7	0.165888	0.161	0.162	0.174665
23.75	0.164	0.165	0.163	0.177463
23.8	0.167274	0.161	0.163	0.177822
23.83	0.16175	0.162	0.1615	0.17454
23.88	0.1635	0.164	0.163	0.173703
23.93	0.165364	0.16	0.162	0.174091
23.97	0.16225	0.163	0.1615	0.173279
24.02	0.166562	0.163	0.163	0.173686
24.07	0.166515	0.161	0.162	0.176545
24.1	0.16325	0.164	0.1625	0.175757
24.15	0.16475	0.165	0.1645	0.178629
24.18	0.166249	0.163	0.164	0.171747
24.23	0.163	0.163	0.163	0.18684
24.28	0.16525	0.166	0.1645	0.175102
24.32	0.16	0.158	0.162	0.168244
24.37	0.161	0.162	0.16	0.174836
24.42	0.165223	0.162	0.162	0.171668
24.45	0.164483	0.161	0.1615	0.17095
24.5	0.162267	0.159	0.16	0.167802
24.55	0.1605	0.161	0.16	0.170768
24.58	0.162433	0.157	0.159	0.171299
24.63	0.1585	0.159	0.158	0.16819
24.68	0.15075	0.148	0.1535	0.167527
24.72	0.154	0.156	0.152	0.168123
24.77	0.157516	0.153	0.1545	0.165048
24.8	0.156	0.157	0.155	0.168088
24.85	0.160176	0.158	0.1575	0.165029
24.9	0.1565	0.156	0.157	0.176614
24.93	0.15675	0.157	0.1565	0.169914
24.98	0.159479	0.157	0.157	0.164438
25.03	0.160504	0.157	0.157	0.167513
25.07	0.165313	0.167	0.162	0.166938
25.12	0.161	0.159	0.163	0.170003
25.17	0.158852	0.155	0.157	0.164557
25.2	0.156504	0.152	0.1535	0.164011

25.25	0.158515	0.159	0.1555	0.161045
25.28	0.154156	0.154	0.1565	0.151969
25.33	0.154904	0.151	0.1525	0.161211
25.38	0.15475	0.156	0.1535	0.164375
25.42	0.1515	0.15	0.153	0.161433
25.47	0.1545	0.156	0.153	0.164595
25.5	0.158391	0.157	0.1565	0.161673
25.55	0.157585	0.153	0.155	0.164755
25.6	0.154652	0.148	0.1505	0.165457
25.63	0.148	0.148	0.148	0.164984
25.68	0.154	0.156	0.152	0.164519
25.73	0.15908	0.156	0.156	0.16524
25.77	0.151824	0.153	0.1545	0.147971
25.82	0.156972	0.155	0.154	0.161916
25.87	0.157356	0.153	0.154	0.165067
25.9	0.15375	0.154	0.1535	0.165832
25.95	0.148	0.146	0.15	0.165401
26	0.15125	0.153	0.1495	0.166205
26.03	0.155766	0.15	0.1515	0.165799
26.08	0.153	0.154	0.152	0.166608
26.13	0.159272	0.158	0.156	0.163816
26.17	0.1535	0.152	0.155	0.167019
26.22	0.15575	0.157	0.1545	0.170246
26.25	0.15325	0.152	0.1545	0.163868
26.3	0.152	0.152	0.152	0.164715
26.35	0.15275	0.153	0.1525	0.166772
26.38	0.156878	0.151	0.152	0.167633
26.43	0.154636	0.149	0.15	0.164908
26.48	0.153199	0.147	0.148	0.164598
26.52	0.1485	0.149	0.148	0.165502
26.57	0.14975	0.15	0.1495	0.165211
26.62	0.15375	0.155	0.1525	0.166124
26.65	0.156611	0.151	0.153	0.165833
26.7	0.14575	0.144	0.1475	0.166761
26.73	0.147	0.148	0.146	0.158117
26.78	0.1465	0.146	0.147	0.169874
26.83	0.1535	0.156	0.151	0.164844
26.87	0.157565	0.151	0.1535	0.168195
26.92	0.151	0.151	0.151	0.165565
26.97	0.153281	0.146	0.1485	0.165344
27	0.14825	0.149	0.1475	0.162748
27.05	0.150717	0.145	0.147	0.160152
27.1	0.1465	0.147	0.146	0.161174
27.13	0.1455	0.145	0.146	0.167
27.18	0.145	0.145	0.145	0.160841
27.22	0.148431	0.143	0.144	0.158292
27.27	0.1445	0.145	0.144	0.155756
27.32	0.148741	0.143	0.144	0.159224
27.35	0.14675	0.148	0.1455	0.162708
27.4	0.14875	0.149	0.1485	0.163785
27.45	0.143	0.141	0.145	0.161267
27.48	0.14175	0.142	0.1415	0.161178
27.53	0.142	0.142	0.142	0.162297
27.58	0.14875	0.151	0.1465	0.156226
27.62	0.136	0.136	0.1435	0.159735
27.67	0.136	0.136	0.136	0.157292
27.7	0.136	0.136	0.136	0.152463
27.75	0.1345	0.134	0.135	0.156043
27.8	0.1325	0.132	0.133	0.153636

27.85	0.135	0.136	0.134	0.157243
27.88	0.133	0.132	0.134	0.16085
27.93	0.132	0.132	0.132	0.158475
27.97	0.1335	0.134	0.133	0.16211
28.02	0.13025	0.129	0.1315	0.162148
28.07	0.13425	0.136	0.1325	0.15981
28.1	0.13675	0.137	0.1365	0.165861
28.15	0.13925	0.14	0.1385	0.163516
28.2	0.1445	0.146	0.143	0.161171
28.23	0.133	0.133	0.1395	0.162416
28.28	0.13375	0.134	0.1335	0.162503
28.32	0.13025	0.129	0.1315	0.163798
28.37	0.13425	0.136	0.1325	0.181916
28.42	0.1345	0.134	0.135	0.167625
28.45	0.1325	0.132	0.133	0.168947
28.5	0.13875	0.141	0.1365	0.169082
28.55	0.13875	0.138	0.1395	0.172803
28.58	0.13275	0.131	0.1345	0.170536
28.63	0.1355	0.137	0.134	0.168298
28.67	0.13625	0.136	0.1365	0.169654
28.72	0.1345	0.134	0.135	0.181819
28.77	0.13925	0.141	0.1375	0.173597
28.8	0.14175	0.142	0.1415	0.159364
28.85	0.139	0.138	0.14	0.175136
28.9	0.1365	0.136	0.137	0.175326
28.93	0.14125	0.143	0.1395	0.173129
28.98	0.1385	0.137	0.14	0.180521
29.03	0.14075	0.142	0.1395	0.178337
29.07	0.14125	0.141	0.1415	0.178547
29.12	0.1425	0.143	0.142	0.170365
29.17	0.1385	0.137	0.14	0.180187
29.2	0.1415	0.143	0.14	0.181632
29.25	0.1445	0.145	0.144	0 185472
29.28	0.142	0.141	0.143	0.18561
29.33	0.1425	0.143	0.142	0.183466
29.38	0.14375	0.144	0.1435	0.183527
29.42	0.14325	0.143	0.1435	0.18469
29.47	0.143	0.143	0.143	0.184763
29.52	0.1415	0.141	0.142	0.188144
29.55	0.138	0.137	0.139	0.183838
29.6	0.137	0.137	0.137	0.18725
29.65	0.13475	0.134	0.1355	0.187371
29.68	0.13775	0.139	0.1365	0.183109
29.73	0.1345	0.133	0.136	0.186541
29.78	0.13675	0.138	0.1355	0.184496
29.82	0.14325	0.145	0.1415	0.182445
29.87	0.134	0.134	0.1395	0.185883
29.9	0.13625	0.137	0.1355	0.183858
29.95	0.125	0.125	0.131	0.187331
30	0.13175	0.134	0.1295	0.187547

Appendix E

Instrumented Synthesis Method [44]

Description of the Method

The starting point of the method is a collapsed-group point-synthesis approximation [45,46,47] in which the NG-element vector ϕ (t) of instantaneous fluxes $\phi_{gn}(t)$ in various energy groups g = 1,2,...,G and reactor regions n = 1,2,...,N is written as a linear combination of K precomputed expansion-functions (or basis-functional $\psi^{(k)}$:

$$\Phi(t) \approx \hat{\Phi}(t) \equiv \sum_{k=1}^{K} \Psi^{(k)} T^{(k)}(t) \quad (1)$$

The expansion functions are chosen as fundamental λ-modes [47,48]. They are generated by performing a series of static critically calculations corresponding to various reactor conditions bracketing the expected transient conditions. The K unknown scalars, $T^{(k)}(t)$, are called "mixing coefficients". They depend only on time. In fact, in Eq. 1, all spatial and spectral effects have been "lumped" into the K expansion vectors $\psi^{(k)}$. The result is a drastic reduction in the number of unknowns from GxN (~ several thousand or more) to K (~ 10).

To facilitate the discussion we introduce an error vector, $\delta\phi(t)$, defined as

$$\delta \Phi(t) \equiv \hat{\Phi}(t) - \Phi(t) \quad (2)$$

a ewrite Eq. 1 as

$$\Phi(t) = \hat{\Phi}(t) - \delta \Phi(t) = \sum_{k=1}^{K} \Psi^{(k)} T^{(k)}(t) - \delta \Phi(t) \quad (3)$$

The main difficulty with Eq. 3 is that a theoretical evaluation of an upper bound for $\|\delta\phi(t)\|$ is not possible in general because of the great flexibility allowed in the choice of the $\psi^{(k)}$'s. Eq. 1 relies on the assumption that, for not-too-fast transients, $\delta\phi(t)$ represents only a small correction to $\hat{\Phi}(t)$ and can therefore be neglected. Since the early days of synthesis methods, there has been considerable numerical evidence to corroborate that assumption. The physical reason for this success is that, for most transients of interest in light-water-moderated reactors, the prompt neutron population readjusts itself very rapidly (in less than a few milliseconds) to changes in the reactor conditions, and this very rapid readjustment (in both shape and amplitude) constitutes the major component of the overall dynamic effects. Other delayed effects (precursor redistribution or delayed feedback effects) leads to only minor changes in flux shape.

Most of the numerical evidence in support of synthesis approximations, however, relied on tests performed only in 1-D or 2-D geometry because of the high computing-costs associated with 3-D finite-difference calculations. Today, modern computers and nodal diffusion codes make these 3-D calculations fairly inexpensive even for desktop machines. Therefore, it is now possible and of interest to assess the validity of Eq. 1 when the $\psi^{(k)}$'s result from 3-D static nodal calculations.

One "standard" way to determine the mixing coefficients, $T^{(k)}(t)$, consists in substituting Eq. 1 into the time-dependent neutron diffusion equation for $\phi(t)$ and in requiring the resulting formula to be true in a weighted integral sense. Alternatively, a variational formulation can be used [45,48]. In either case, the result is a set of K first-order, nonlinear, ordinary differential equations for the $T^{(k)}$'s. In principle, finding a numerical solution to these equations is not too difficult provided all initial conditions are known. However, the determination of the various coefficients appearing in these equations (in the form of integrals) is not an easy task in general. In fact, some integrands

cannot be properly computed unless extra unknowns and additional equations are introduced.

The present method is an attempt to avoid these complications by determining the $T^{(k)}$'s in a more direct way. Rather than using global, theoretical information as in the above integral methods, local, experimental information in the form of flux-measurements is used. This is possible if one assumes that the reactor is equipped with a number of fixed, fast-responding, in-core neutron detectors (of the 'fission chamber' or 'prompt self-powered' type), each characterized by a known response-function. The output, $C^{(j)}(t)$, of the j-th detector under a flux $\phi(t)$ is written as

$$C^{(t)}(t) = \sum_{g=n}^{G} \sum_{n=1}^{N} V_n \Sigma_{g_n}^{(j)} \Phi_{g_n}(t) \; ; \; j = 1,2,\ldots,J \tag{4}$$

or equivalently, using an inner-product notation,

$$C^{(j)}(t) = \Sigma^{(j)^T} \Phi(t) \; ; \; j = 1,2,\ldots,J \tag{5}$$

The cross sections $\Sigma_{g_n}^{(j)}$ in Eq. 4 result from homogenization calculations. The summations have been extended to the entire core volume and neutron energy-spectrum, with the convention that $\Sigma_{g_n}^{(j)}$ are zero outside the homogenization region. These homogenized response-functions vary only slowly with time and no time-dependence is shown explicitly. V_n is the volume of node n and has been absorbed in each element of the row vector $\Sigma^{(j)^T}$ in Eq. 5.

Eq. 5 is a set of J "observation equations". For notation convenience, these equations as well as Eq. 3 are recast in matrix form as

$$\Phi(t) = \hat{\Phi} - \delta\,\Phi(t) = \Psi\,T(t) - \delta\,\Phi(t) \tag{6}$$

and

$$\Sigma^T\,\Phi(t) = C(t) \tag{7}$$

In the above matrix notation, ψ and $\sum$ are GN-by-K and GN-by-J rectangular matrices respectively. Substitution of Eq. 6 into Eq. 7 yields

$$\Sigma^T\,\Psi\,T(t) - \Sigma^T\,\delta\,\Phi(t) = C(t) \tag{8}$$

or simply

$$A\,T(t) + E(t) = C(t) \tag{9}$$

where

$$A \equiv \Sigma^T\,\Psi \tag{10}$$

is a J-by-K matrix with positive entries (each entry is an inner product), and

$$E(t) \equiv -\,\Sigma^T\,\delta\,\Phi(t) \tag{11}$$

is a column vector of length J of systematic errors. If one assumes that the unknown error-vector $\delta\,\Phi(t)$ in Eq. 6 is small with respect to $\hat{\Phi}(t)$ (in the sense of some vector

norm), then E(t) is also small with respect to A T(t) in Eq. 9. In these conditions, Eq. 9 can be rewritten as

$$A\,T(t) \approx C(t) \tag{12}$$

If A could be "inverted" (once and for all), then Eq. 12 could be solved for T(t) every time signals are received from the instrumentation. However, in general, $J \neq K$ and therefore A is not square and cannot be simply "inverted". Nevertheless, a minimum-norm least-squares solution, $T_{LS}(t)$, can always be found. This least-squares solution can be substituted in Eq. 6 to determine $\hat{\Phi}(t)$. From this reconstructed flux-vector, integral quantities such as fission power, amplitude function, and reactivity (inverse kinetics) can be computed [47]. This procedure appears quite straightforward and can be expected to be fast and fairly inexpensive.

In fact, this simple idea of directly fitting precomputed expansion-functions to detector readouts is not new [49,50,51,52,53,54]. However, it seems that no result involving 3-D nodal expansion-functions has ever been reported. In addition, a number of difficulties with this procedure have not always been recognized.

A first difficulty is with the error term, $\delta\,\Phi(t)$, because as already mentioned no theoretical estimate is available to quantify this error. This is a direct consequence of the fact that, in general, no restriction is placed upon the method used to generated the expansion functions $\psi^{(k)}$, and , once a method has been chosen, no prescription is given for selecting the particular reactor-configurations for which basis functions should be computed. On the other hand, this great amount of flexibility is also the key to the success of the flux-synthesis idea.

Other potential sources of difficulties are uncertainties in the $\Sigma^{(j)}$'s which may lead to systematic errors in both A and C(t) (Eq. 7). Errors of numerical of physical origin in the $\psi^{(k)}$'s may worsen this bias in A. In addition, the vector C(t) will unavoidably contain random errors from measurement noise.

An additional, potentially serious, numerical problem arises from the fact that some of the expansive functions, $\psi^{(k)}$, making up the columns of the matrix ψ may be almost linear combinations of other expansion functions. As a result, the matrix $A = \Sigma^T \psi$ may be very ill-conditioned, i.e. almost rank-deficient. In some extreme cases, this ill-conditioning may lead to a least-squares solution of Eq. 12 which is completely meaningless because of roundoff-error amplification. The same problem may arise from row-redundancies when only a reduced number of detectors is used with symmetries both in their locations and in the core composition pattern.